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SUMMARY TECHNICAL REPORT OF THE NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 17

Underwater Sound Equipment IV

FREQUENCY-MODULATED SONAR SYSTEMS

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him—some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

SEARCHLIGHT echo-ranging systems of the type employed by the American and British Navies throughout the war suffer from the limitation that at no instant does that method provide complete information as to the presence of all underwater objects within sound range. The Division accordingly authorized studies and development by Harvard University and the University of California upon what has been termed "scanning sonar" capable of presenting simultaneous information in range or bearing.

The developments undertaken by the Harvard Underwater Sound Laboratory are fully reported upon in Volume 16 of this series, *Scanning Sonar Systems,* prepared by Dr. F. V. Hunt. This volume, *FM Sonar Systems,* prepared under the direction of Dr. Franz Kurie, reports the development undertaken by the San Diego laboratory under direction of Division 6 until March 1, 1945, and since that date under direction of the Bureau of Ships.

It was recognized that these were projects of a long-term nature and that in view of the several time-factors involved apparatus employing the methods in question might not find employment in the present war. Actually, however, the FM sonar equipment developed by the San Diego laboratory was installed upon a number of submarines and was successfully employed in a critical operation in the Pacific area.

The Division is appreciative of the efforts of Dr. Kurie and his associates in preparing this report and also wishes to acknowledge its obligation to the Navy, which generously permitted the authors to complete the report after transfer of the San Diego laboratory to the direction of the Bureau of Ships.

Beginning in 1941 the Navy provided facilities without which it would not have been possible to continue effectively this development. In the Bureau of Ships, Captain Rawson Bennett, Jr., maintained for several years most helpful liaison with the project. Later, Commander J. C. Myers continued this close and cordial contact with the work under way. Certain less formal contacts with Navy operating personnel were also most helpful and stimulating to the laboratory staff.

The Division fully realizes that only a good beginning has been made in the development of scanning sonar. Much in the way of study and experimentation is still necessary to determine its possibilities and to a choice of the most effective methods. To enable the Navy to continue the program with reasonably complete information as to the results already accomplished, the Division has felt to be justified the more than ordinarily detailed summary reports referred to above.

JOHN T. TATE
Chief, Division 6

PREFACE

THIS REPORT concerns work done by the University of California Division of War Research for Division 6 of the National Defense Research Committee under the Office of Scientific Research and Development Contract OEMsr-30, and for the Navy Department under Contract NObs-2074 at the request of the Bureau of Ships. The FM sonar systems program was undertaken in the fall of 1941, shortly after UCDWR was organized, as a part of Navy Project NS-142 for the general improvement of echo-ranging gear. On March 1, 1945, auspices of the program were transferred directly to the Bureau of Ships and the project was carried on as Task 3 Problems 3A and 3B under the new Navy contract. Invention Reports PC-4 sr-30 Patents 12, 14, 23, 28, 29, 45, 46, 47, 54, 76, 80, 81, 89, and 114 cover some of the QLA systems information set forth herein. Other Invention Reports PC-4 sr-30 Patents 95 and 113 pertain to an associated device, the QLA simulator trainer.

The project was initiated under the sponsorship of K. S. Van Dyke, and toward the end of 1942 became an important activity of the Sonar Devices Division of UCDWR. As project leader, M. C. Henderson was in supervisory charge of this work throughout most of the war. C. A. Hisserich who originated the Fampas idea, S. Bertram who devised the electronic switch used in QLA sonar, and M. O. Kappler who, through his close association with the Submarine Force, Pacific Fleet, introduced important improvements into the system, are deserving of particular mention. The following individuals made valuable contributions to the development of FM sonar systems: F. Baltzly, Jr., T. F. Burke, R. O. Burns, C. R. Hauser, J. N. A. Hawkins, W. W. Isenberg, E. J. Lark, C. G. McProud, A. A. Osterman, B. A. Penners, M. C. Poche, A. H. Roshon, Jr., J. W. Sampsell, I. C. Simpson, Jr., K. J. Takle, R. L. Waldie, D. O. Williams, G. V. Williams, W. H. Williams, and K. K. Wyckoff.

F. N. D. KURIE
Editor

CONTENTS

Chapter 1

INTRODUCTION TO FM SYSTEMS

ECHO-RANGING SOUND GEAR is today universally used by the navies of the world. Sound, sonic or supersonic, is projected into the water, and, from the returning echoes, it is possible to determine the presence, location, and even the character of vessels or other objects. One type of such echo-ranging equipment utilizes frequency-modulated [f-m], continuously-

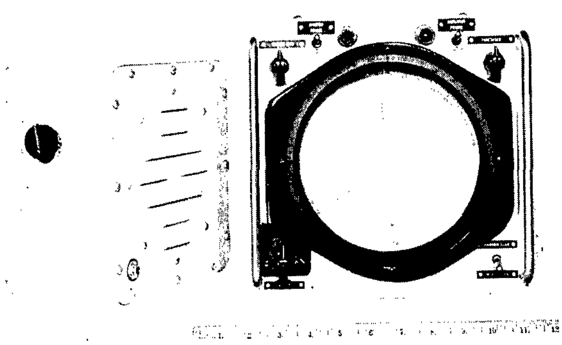


FIGURE 1. FM systems (here, QLA) differ from older types of underwater sound equipment in the method of presenting information: Both audibly (left) by tones through a loudspeaker, and visually (right) on a cathode-ray oscilloscope [CRO] screen.

radiated sound for locating underwater objects, and is covered by the generic term, frequency modulation [FM] systems.

1.1 WHAT IS FM SONAR?

As of the date of this report, the FM systems program has culminated in a device known by the Navy designation of QLA sonar. The following nontechnical, pictorial explanation of an FM system details the operation of QLA sonar. While the specific values contained in the explanation—frequencies, number of analyzer channels and their widths, sawtooth form of frequency modulation and width of modulation band, range scales, etc., are peculiar to one specific QLA system, the basic functions portrayed are true of any FM system.

1.2 ADVANTAGES OF FM SYSTEMS

There are certain advantages of tactical importance which are inherent in the FM system method of operation in echo-ranging. Since the radiated sound is of a continuous nature, every target within the range of the sound beam becomes, itself, a source of continuous sound. Thus, FM echo ranging becomes in essence a listening operation. It is from the continuous nature of the echoes produced in FM echo ranging that most of the advantages of FM systems spring.

Automatic, Rapid Search. FM practice is to "floodlight" an area with transmitted sound and to scan within the floodlighted area with a hydrophone of narrower beam. With a projector

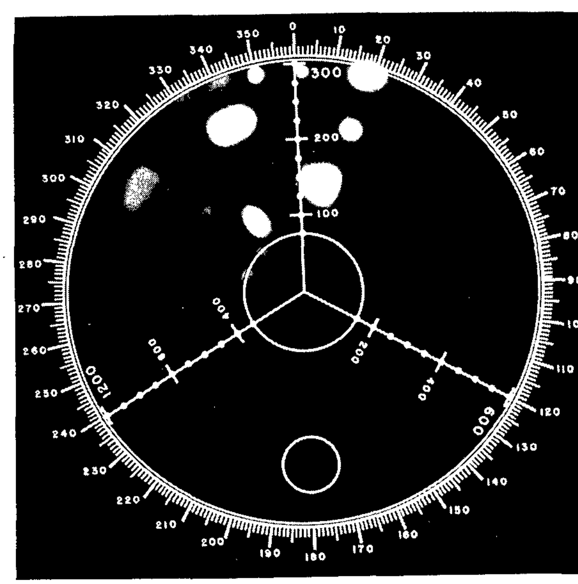


FIGURE 2. A typical visual presentation of the field on the oscilloscope. The operating ship is in the center of the screen, and the illuminated spots represent various echo-reflecting objects.

beam of sufficient width, scanning with FM systems becomes a matter of training the hydrophone. Under these conditions the range scan of FM systems is almost instantaneous, and the bearing scan has been found adequate for the tactical requirements obtaining in World War

II. The rate of bearing scan of QLA-1 can be increased, if desired, with certain modifications. See Section 2.2.1.

Simultaneous Portrayal of Several Targets. With the current long-persistent-screen *cathode-ray oscilloscope* [CRO] it is possible to portray several targets simultaneously at various bearings and ranges. Targets existing on the same bearing but at different ranges are portrayed with a facility equal to that possible for targets at various bearings and at the same or different ranges. Such a portrayal is of considerable value in any tactical situation in which there are numerous targets within the maximum range of the system. One important application of this feature is its use in navigation through mine fields by surface or underwater craft.

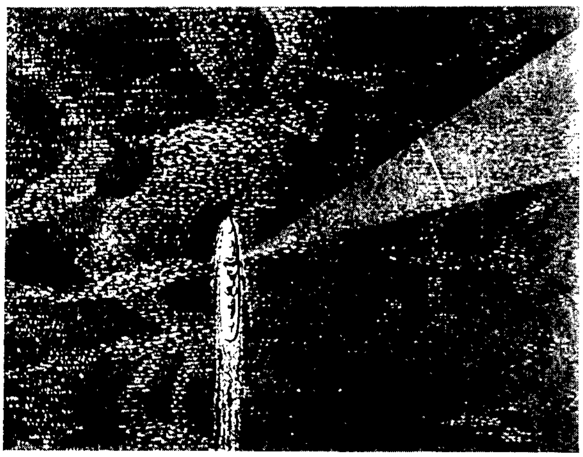


FIGURE 3. The old procedure was the familiar "ping, listen, and train" operation with intermittent signal on a single frequency.

Ease of Maintaining Contact. Because of the continuous nature of echoes obtained with FM systems, it is possible, once a target has come within range, to maintain contact with it continually throughout any maneuver.

Determination of Target Character. The continuous nature of the echo received with FM systems makes it possible to differentiate between various types of targets; for example, both the CRO trace and the loudspeaker tone arising from a mine (as a target) differ from the indication returned by kelp.

Availability of Tactical Information. The persistent trace on the CRO screen gives a record of the immediate past history of any target maneuver, making it possible to predict, in some degree, the future moves of an adversary. For a more permanent record, a maneuvering board or a chemical recorder may be used in conjunction with the FM system.

Averaging of Echoes. With each target a continuous source of sound, FM systems average an infinite number of minute indications received from any one target. Averaging makes for rapid scanning in both bearing and range. To understand how this is possible, it is necessary to consider, for a moment, conventional pinging gear; the fate of a particular ping and its echo is a function of many variables associated with its acoustic path. Most of these change rapidly both with time and with frequency, particularly at longer ranges. The echo which any outgoing ping returns to the receiver, therefore, is subject to violent fluctuations: differences of as much as 20 db between successive pings are occasionally encountered. The consequences of this irregularity are a serious problem in pinging systems. For example, suppose a particular ping has a one-quarter chance of being heard at the receiver after reflection from a target. Then, on the average, four pings have to be sent in one direction before any indication of the target's presence is received. In the case of an FM system which is sector-scanning within the beam of the hydrophone, indication of the target's presence under these same conditions is received one-quarter of the time; but, since the fluctuations in echo strength are rapid, about one-quarter of each modulation cycle gives an indication of contact. Hence, with the long-persistent screen on the CRO, FM systems even under these conditions exhibit relatively continuous target indication.

Relative Immunity from Countermeasures. An FM system is relatively difficult to jam with a narrow-band noisemaker, because its operating frequency sweeps over a relatively wide band. As long as the CRO screen is not too persistent, disturbance occasioned by narrow-band noisemakers does not interfere materially with discovery and identification of targets.

High Signal-to-Noise Ratio. The splitting of FM system receiver output in passing it through 20 separate filter channels makes it

possible for each filter to be narrow enough to discriminate against background noise. This procedure results in a system with a high signal-to-noise ratio.

Small Object Detection. Investigations conducted during the latter part of World War II indicate that pinging systems require the use of extremely short pulse lengths in order to detect small objects such as mines. The use of pulse lengths of the order of 1 msec or less necessitates a proportionate increase in the bandwidth of the receiver and results in a low signal-to-noise ratio.

FM systems, on the other hand, can effectively approach these short pulse lengths by *reducing* the width of their present filter channels. Such a change would improve instead of decrease FM signal-to-noise ratio, though it would limit to some extent the maximum practical speed (a limit which is not reached in the present FM system, QLA-1) at which bearing may be scanned.

Definition at Extremely Short Ranges. Because of the frequency sweep in the transmitted signal of FM systems and the practice of blanking transmission and receiver at the instant of flyback, it is possible to scan and determine range on targets within a few yards of the echo-ranging vessel. This is a distinct advantage in certain navigational problems, notably maneuvering through mine fields, and is a feature peculiar to FM in that a signal emitted by any pinging type of gear produces reverberation of such a nature that detection of echoes from ranges less than 300 to 400 yd is exceedingly difficult.

Continuous and Easy Monitorable Tone. Aural presentation of target information as a continuous and easy monitorable tone reinforces the visual presentation of information on targets in all the applications described above.

1.3 COMPARISON OF FM SYSTEMS WITH PINGING SYSTEMS

1.3.1 Characteristics of Pinging Systems [QC]

Ping-train-listen types of gear send out a pulse of sound which, in some types of QC sonar using a 15-in. diameter piston uniformly driven at 24 kc, extends over a relatively narrow beam, approximately 10 to 12 degrees wide at the 3-db down points. Following the emission of the ping, and for a period of time required by the ping in traversing the distance from the echo-ranging ship to the maximum range and back, it is necessary to wait (listen) in order to determine whether or not there is a target within that range and within the 18- to 20-degree sector over which the ping is effective. The duration of this waiting period, as determined by the transmission speed of sound in water, is approximately 2 sec per mile of distance between the echo-ranging vessel and the target.

The soundhead is trained approximately 5 degrees to the right or left between pings, and this cycle of ping-train-listen is repeated until the prescribed search sector has been covered, or until a contact is made with a target. *Bearing deviation indicator* [BDI] modifications of this type of gear make possible fairly rapid bearing determination once contact has been made with a target but do not directly increase searching speed.

When an echo reaches the QC projector-hydrophone, it is amplified in a tuned receiver to minimize background noise. Because QC pings are in supersonic frequencies, after amplification they are heterodyned down to an audible level so that they may be monitored by means of a loudspeaker or earphones.

No attempt at the scanning type of *plan position indicator* [PPI] presentation of target information has been made with standard gear; but in those systems having BDI modification, deviation of target bearing from the normal relative bearing of the hydrophone beam pattern is indicated on a CRO.

1.3.2 Characteristics of Pinging Systems [QHA-CR and ER]

One type of pinging gear, the QHA system, is a scanning sonar. QHA systems may be designated as *capacitor rotated* [CR] or *electronically rotated* [ER] and differ only in the method of scanning.

A typical system of this type sends out a pulse in all directions, then scans for returning

echoes with a rapidly rotating, directional, receiving beam. The returning sound is received in many separate fixed hydrophones mounted on a cylinder. These hydrophones are connected by phasing networks to make the receiving beam directional. By use of a mechanically rotating commutator system in CR, and electronic commutation in ER, this receiving beam is rotated continuously about the horizon at the rate of at least 360 degrees of bearing for every pulse length. Returning echoes from all bearings are portrayed on a cathode-ray screen. Thus, targets at any range within the maximum range and at any bearing should in principle be detected by the system. Since the returning echo is at least a pulse length long, and since the receiving beam is rotated through the entire horizon during the time interval occupied by each pulse, the echo should be perceptible during some small fraction of a pulse length. In the system of present design, the outgoing pulse is 35 msec long. Thus, all bearings are scanned once every 35 msec, and each range out to the maximum range is scanned once for every emitted pulse. The range being scanned at any instant is determined by the velocity of sound; it is zero at the instant the pulse is put into water, and increases at a rate of 800 yd of range per sec. Since a relatively narrow receiving beam is used, only a very small segment of the 35-msec length of echo is actually received; in fact, the duration of the received echo is about 1 msec. This short echo requires a receiver bandwidth about 1 kc in width (so that the filter may be responsive to this short signal) and hence the ratio of signal-to-noise is low.

1.3.3 Characteristics of FM Systems [QLA]

With FM sonar, on the other hand, a steady signal is sent out over a wide sector which in present gear is 80 to 90 degrees wide. The operation of FM(QLA) systems is illustrated in Figures 4-35. The frequency of the outgoing signal decreases steadily with time for a period of less than 1 sec to several seconds (depending on the range for which the equipment is set) after which the frequency increases abruptly to its initial value and another cycle begins. At any one time, the frequency of the received echo depends on the range; the difference in frequency between the outgoing signal and the echo from a fixed range is a constant if the frequency sweep is linear, and is directly proportional to the range. In practice the echo is heterodyned against the outgoing signal, and it is the difference frequency which is actually used for detection of the echo. The receiving system is provided with many different filters so that echoes from all ranges at a given bearing can be portrayed simultaneously on a cathode-ray screen, each filter receiving echoes from a certain level of range. The relatively narrow width of the filters (each 75 c wide) results in a high signal-to-noise ratio in comparison with systems using wider filters. Gear of present design employs a directional, trainable, receiving transducer which is rotated mechanically so that any given sector can be scanned in a fraction of a minute. Since the projector is also somewhat directional, this is mounted on the same shaft and is rotated with the receiver. Thus the roles of range and bearing are reversed in FM as compared with CR. In CR, different bearings are presented almost simultaneously while range is slowly scanned; in FM, different ranges are presented simultaneously while different bearings are slowly scanned. It is clear that for a fixed target, the FM systems give continuous range information while CR sonar gives ranges only at intervals (depending on the range) up to several seconds.

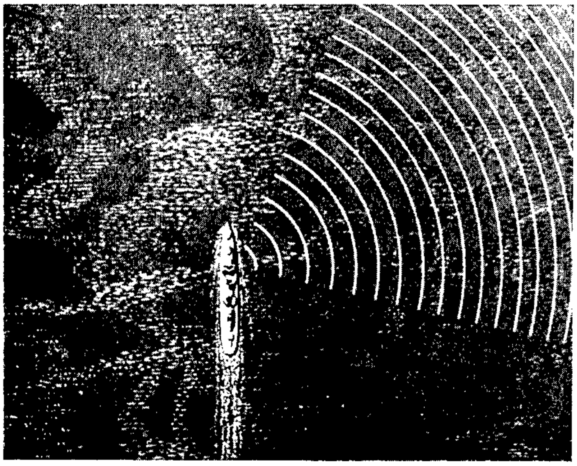


FIGURE 4. QLA sonar sends out continuous, supersonic sound waves of *varying* frequency and trains *continuously* and *automatically*. The search arc can be controlled by the operator to scan any desired sector.

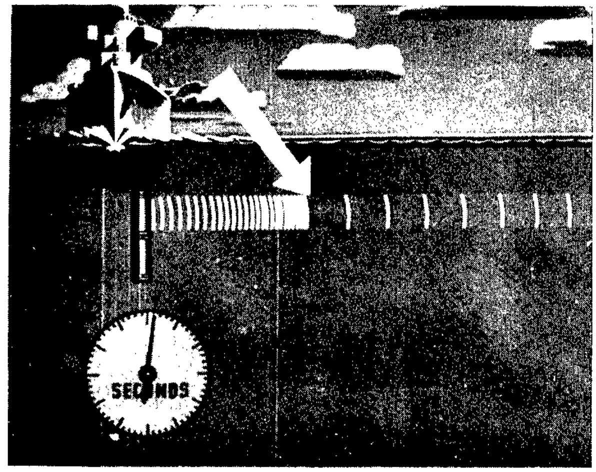


FIGURE 6. The frequency then returns abruptly to the maximum value (see arrow) and the cycle is repeated. The instant at which the frequency returns abruptly from minimum to maximum is called the flyback period.

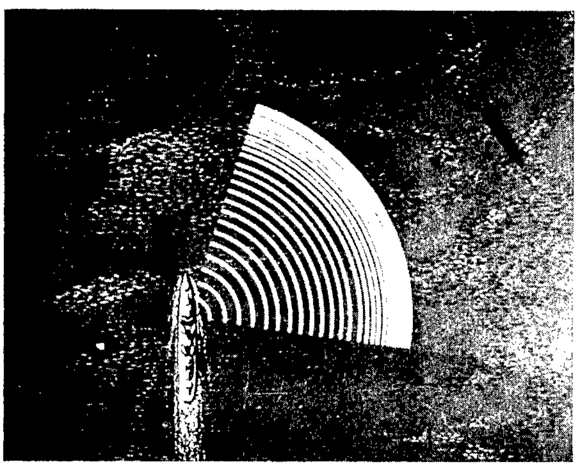


FIGURE 5. The frequency of the sound leaving the QLA sonar projector varies uniformly with time. Beginning at a maximum, it decreases uniformly throughout the modulation cycle until, 1 sec to 30 sec later, at the end of the cycle, it reaches the minimum.

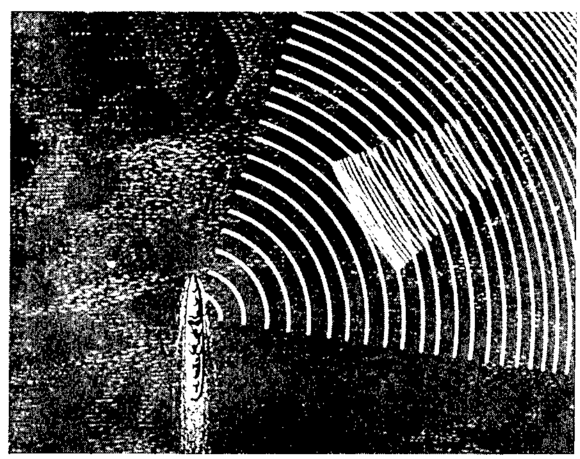


FIGURE 7. Here the wave front of the echo may be observed returning from a submarine. By the time the maximum-frequency wave front of the echo returns to the receiver, the steadily decreasing frequency being emitted by the projector has reached a point several cycles per second below its peak initial frequency.

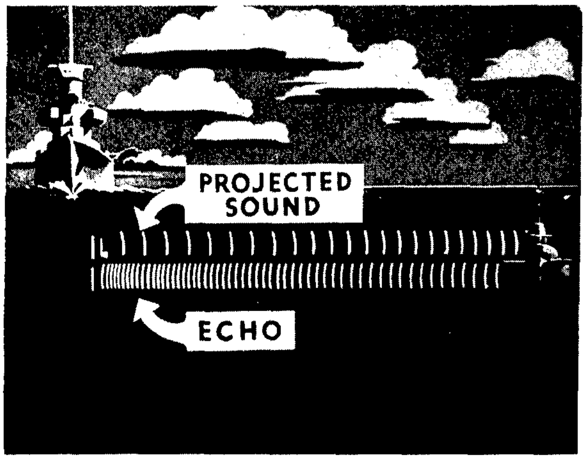


FIGURE 8. In the cross-sectional view of the situation illustrated in Figure 7, it is apparent that the difference in frequency between outgoing sound and incoming echo is a measure of the range of the reflecting submarine.

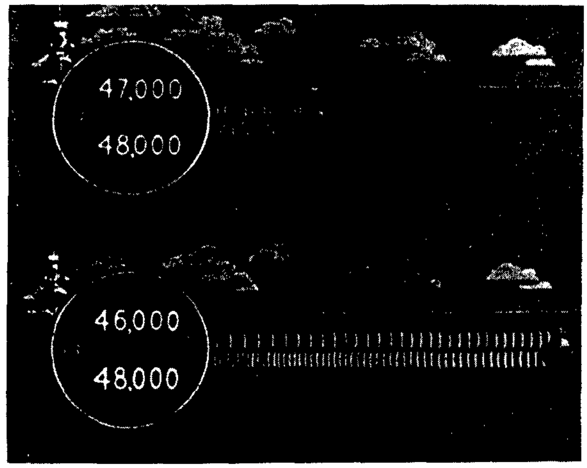


FIGURE 10. It follows that the greater the range, the greater the difference between frequency of outgoing sound and frequency of incoming echo. In the top picture, the difference is 1,000 c; in the bottom, 2,000 c. The range in the bottom picture is thus shown to be twice as great as the range in the top illustration.

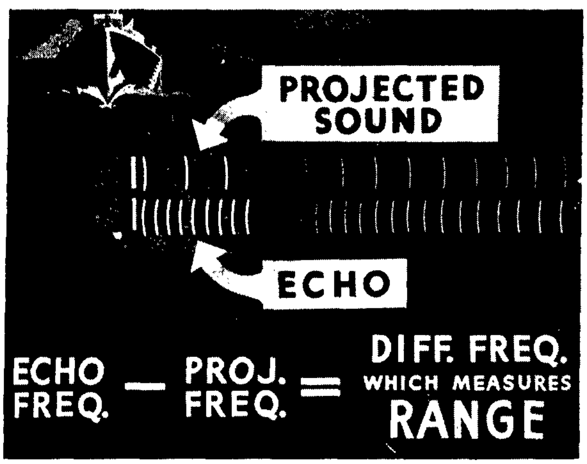


FIGURE 9. Expressed simply: Echo frequency minus projected frequency equals difference frequency, which measures range.

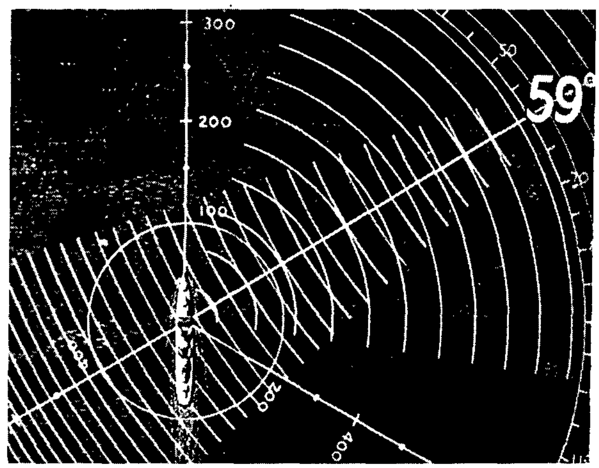


FIGURE 11. Not only is the range determined by QLA sonar as described above, but the bearing is also indicated by the direction from which the echo is received.

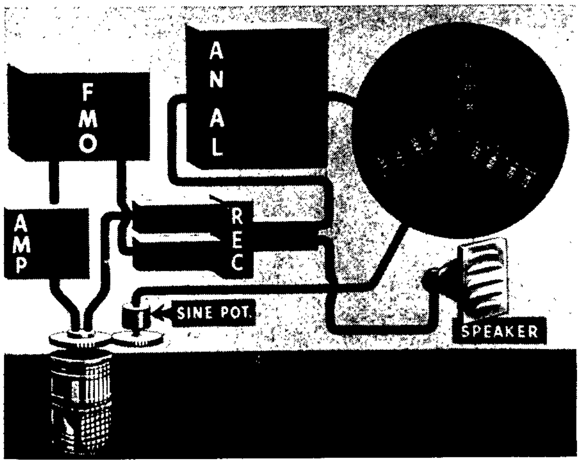


FIGURE 12. This simplified schematic diagram of the various components of QLA sonar shows how each functions in relation to the entire installation.

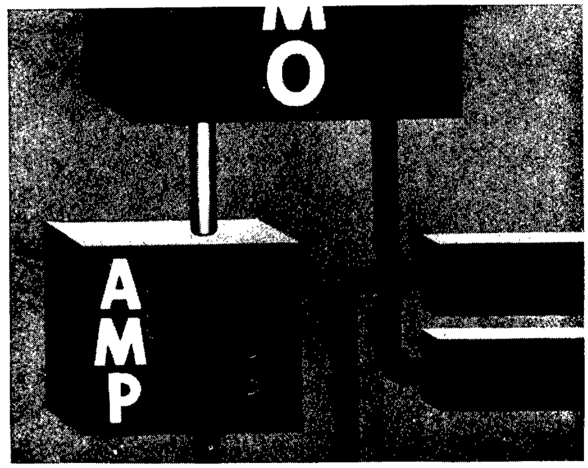


FIGURE 14. The output of the f-m oscillator is fed to a power amplifier where the oscillations are amplified to a useful level and then sent to an underwater projector.

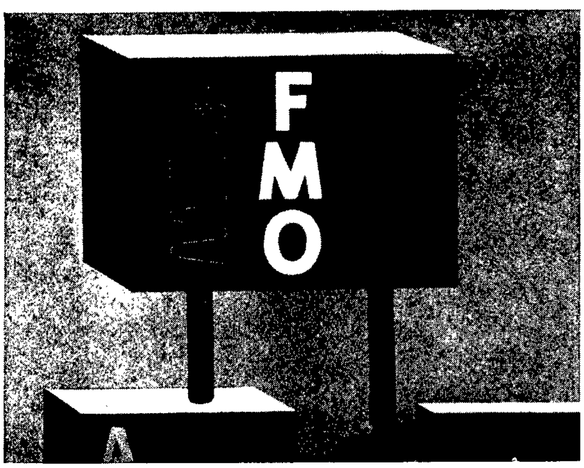


FIGURE 13. A frequency-modulated oscillator generates alternating electric current at supersonic frequencies, starting at a maximum frequency of 48,000 c and gradually decreasing to a minimum of 36,000 c, thereby completing a modulation cycle. This cycle is repeated continuously.

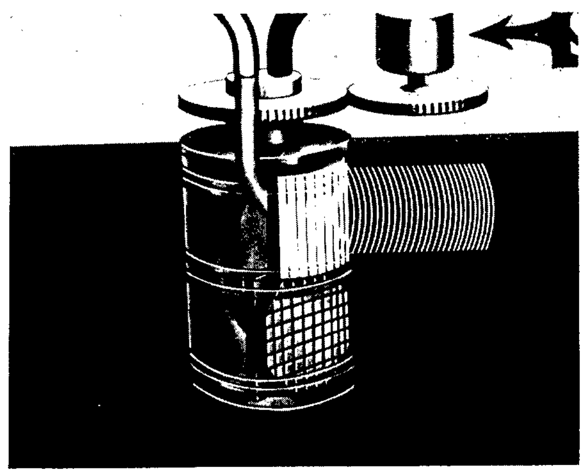


FIGURE 15. In the projector, piezoelectric crystals convert the electric energy into sound waves which are radiated from the projector face into the water. The projector is located in a soundhead with the hydrophone unit.

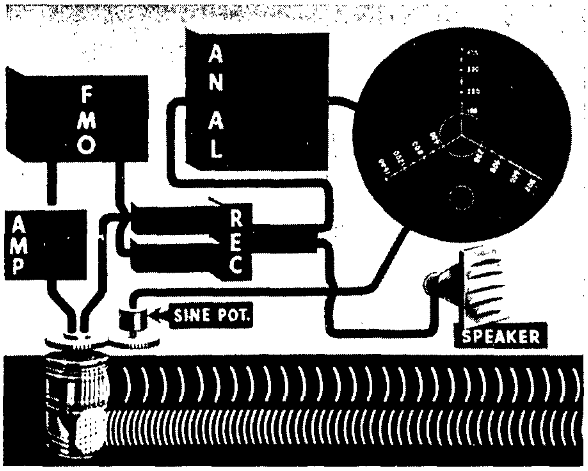


FIGURE 16. The hydrophone picks up the returning echoes and its piezoelectric crystals convert them back into electrical energy. This electrical energy, at frequencies representing the reflected echoes, goes to the receiver.

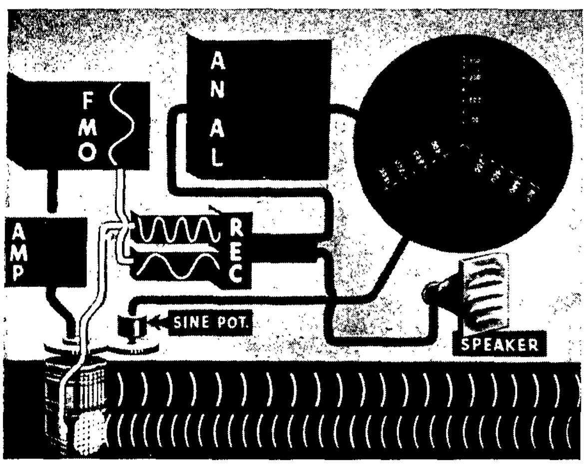


FIGURE 17. In the receiver, the echo signal is mixed with a sample of the frequency being fed from the oscillator at the exact moment at which the echo arrives. In effect, the receiver subtracts one frequency from the other to obtain the difference-frequency. The difference-frequency tells the range of the reflecting object.

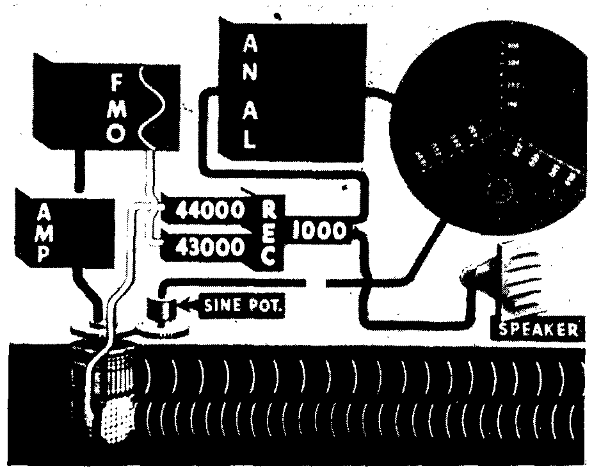


FIGURE 18. These difference-frequencies evolved by the receiver (see large white arrow) then go to the analyzer and loudspeaker.

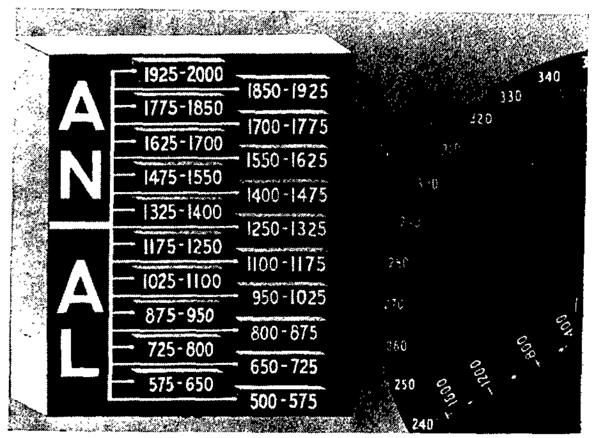


FIGURE 19. The QLA analyzer has 20 channels. Each channel is capable of passing a 75-c band of frequencies, graduating from 500 c to 2,000 c.

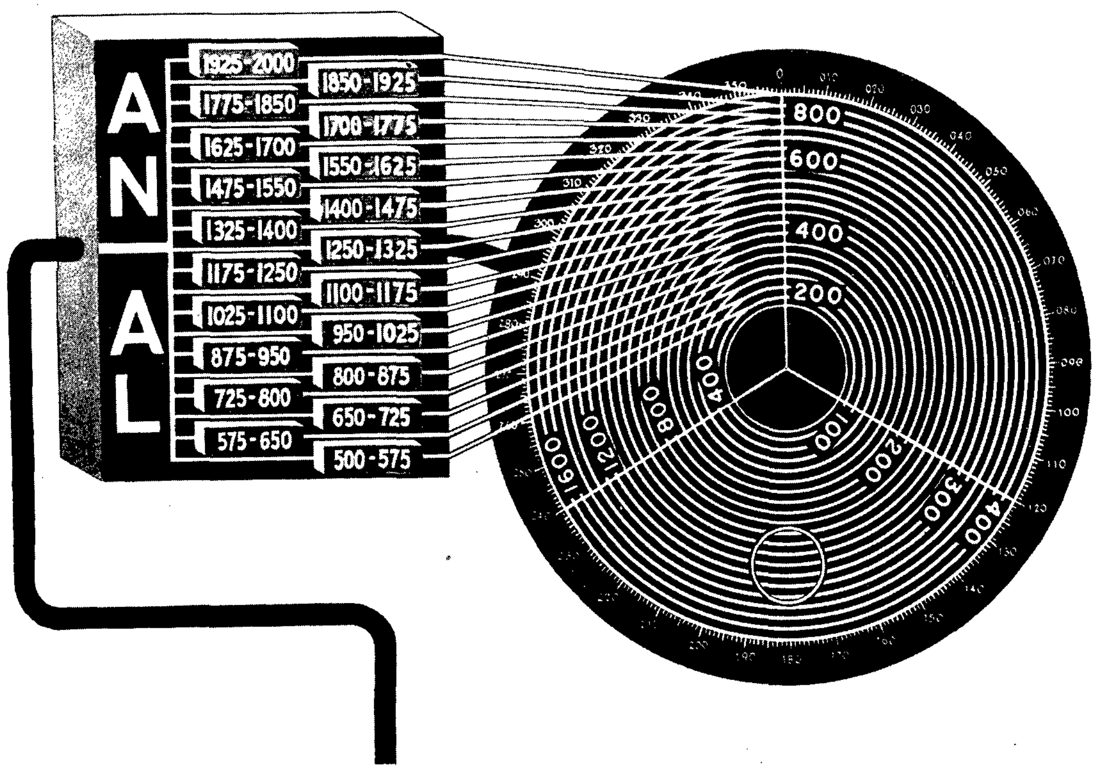


FIGURE 20. For each of these 20 channels there is a corresponding concentric band on the circular screen of the CRO.

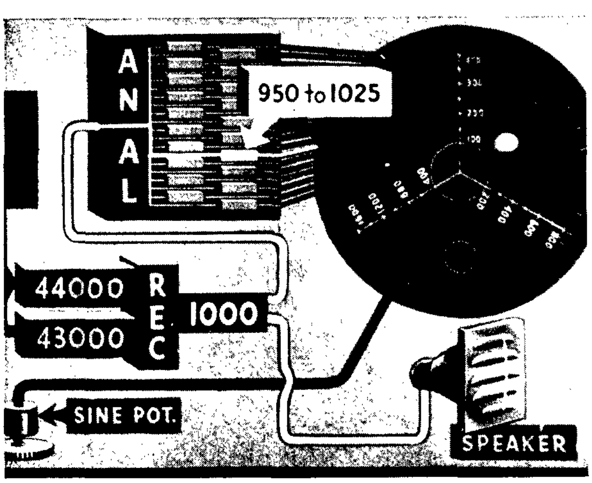


FIGURE 21. A particular frequency, indicative of a specific range, is accepted by the appropriate channel of the analyzer (as illustrated for the 950-c to 1,025-c channel above). It then appears as a light spot on the corresponding band of the oscilloscope screen, and, simultaneously, as an audible tone from the loudspeaker.

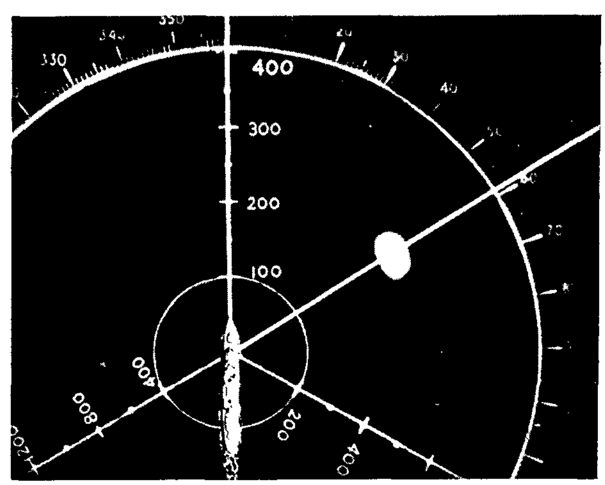


FIGURE 22. The relative bearing at which the spot appears on the screen coincides with the relative bearing of the hydrophone at the instant it received the reflected echo. The vertical center line of the screen corresponds to the heading of the echo-ranging vessel.

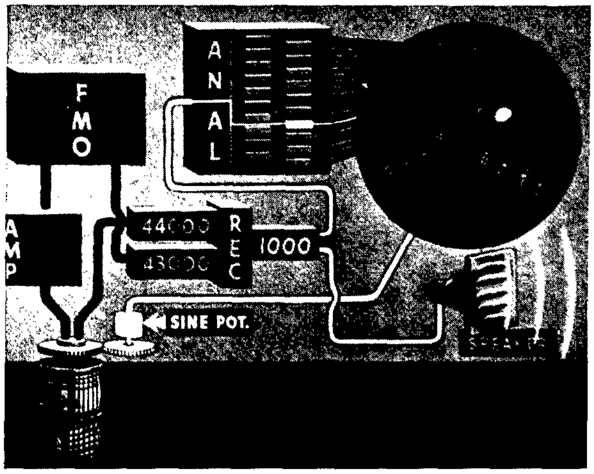


FIGURE 23. The bearing orientation of the spot, or trace, on the screen is achieved by coupling a sine potentiometer to the hydrophone column. As the soundhead rotates, each returning echo and its difference-frequency produce a corresponding spot on the screen and tone from the loudspeaker.

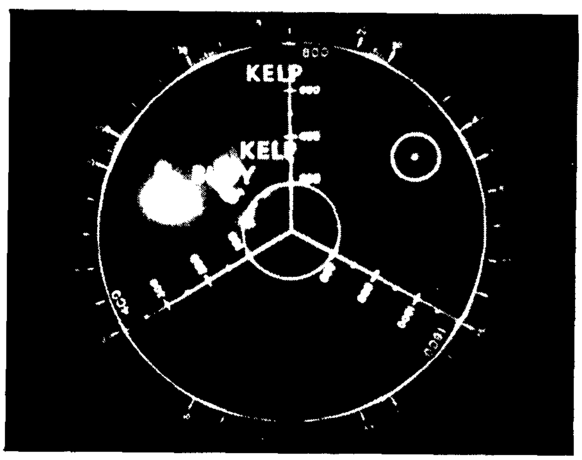


FIGURE 24. The scanning action of the soundhead traces on the oscilloscope a plan view of the area surrounding the ship. Every reflecting object in the area that returns an echo of sufficient strength is represented both visually and audibly.

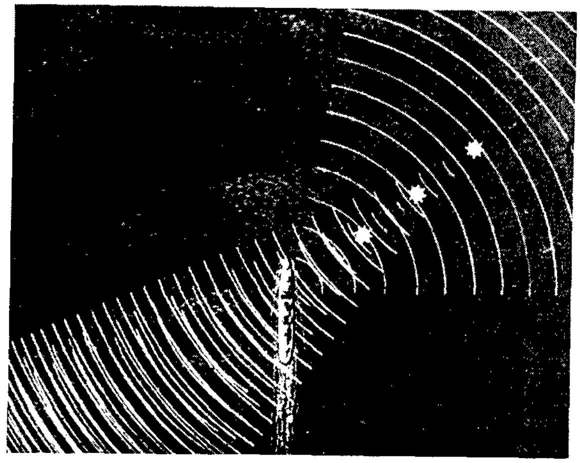


FIGURE 25. Even objects at the same bearing but at different ranges are represented simultaneously. Compare this diagram with the corresponding oscilloscope picture in Figure 26.

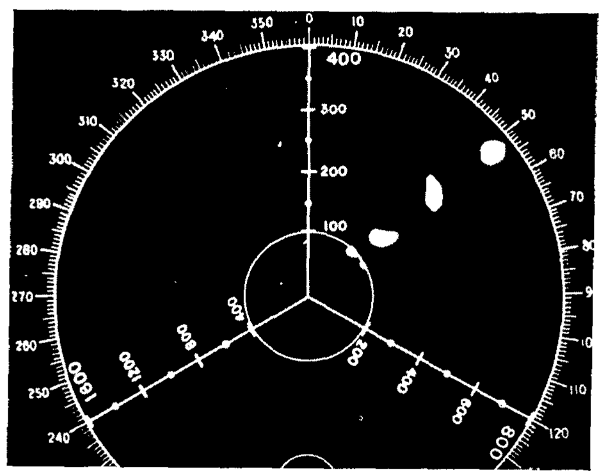


FIGURE 26. Field conditions diagramed in Figure 25 would appear on the CRO screen as shown above. The sine potentiometer simultaneously orients a number of objects at the same bearing, but at different ranges.

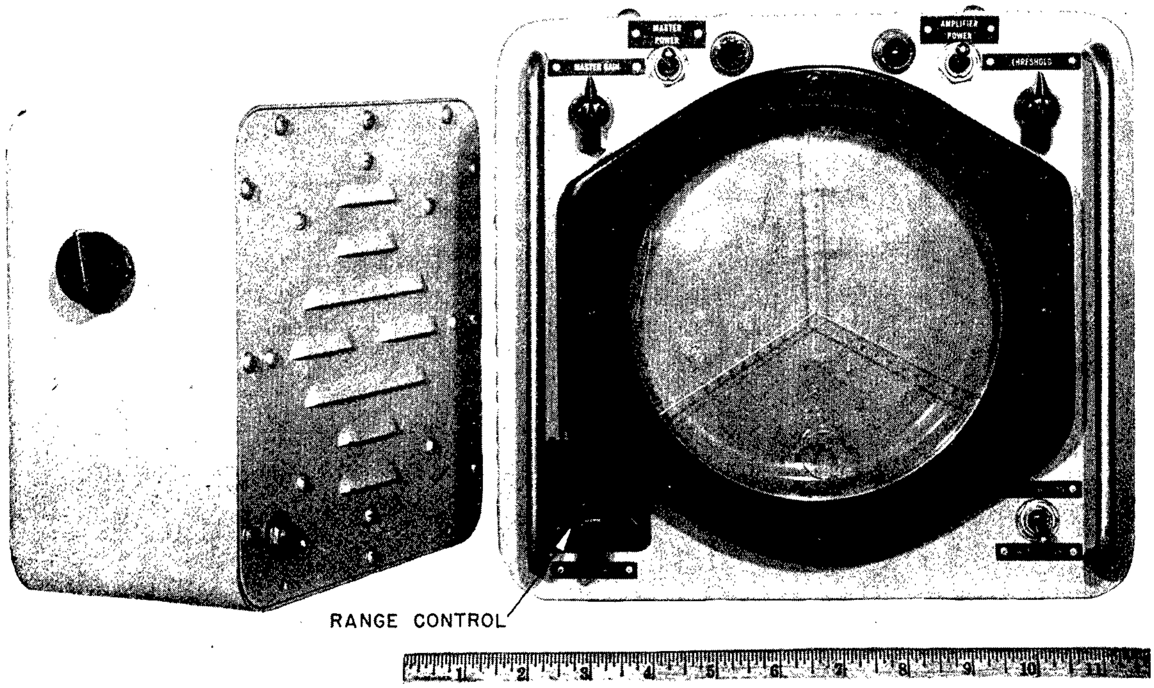


FIGURE 27. QLA sonar may be operated at any one of the several different maximum ranges at the option of the operator. The outer limits of the indicator screen then represent maximum ranges of 400 ft, 400 yd, 800 yd, 1,600 yd, or 4,000 yd depending upon the range for which the system is set.

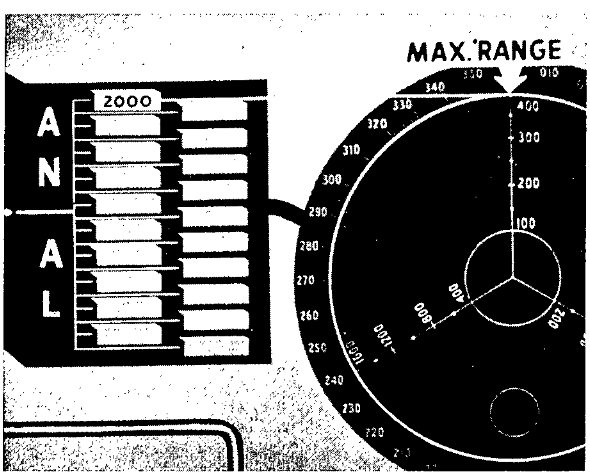


FIGURE 28. In order to understand how the outer limit of the indicator screen can be made to represent several different maximum ranges, one must reconsider for a moment the analyzer and its channels. Since 2,000 c is the maximum frequency acceptable to the analyzer, this 2,000-c difference frequency represents the maximum range at which a target can be shown on the indicator screen.

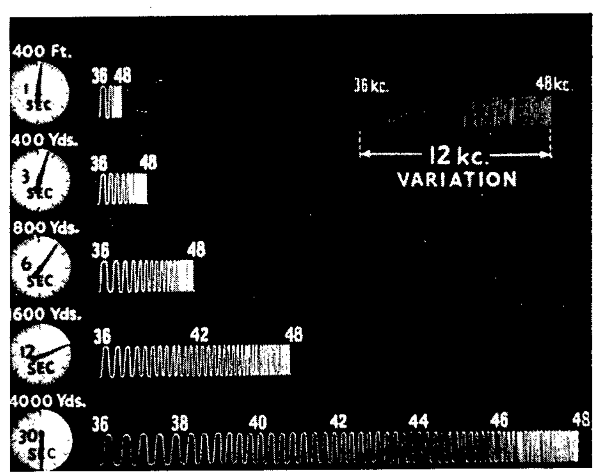


FIGURE 29. The 2-kc difference frequency can be made to represent several different maximum ranges by changing the rate of varying oscillator frequency. Because limits of frequency variation are fixed, changing the rate automatically changes the duration of the cycle. This may be changed from 1 to 30 sec by different stages, depending on the range chosen.

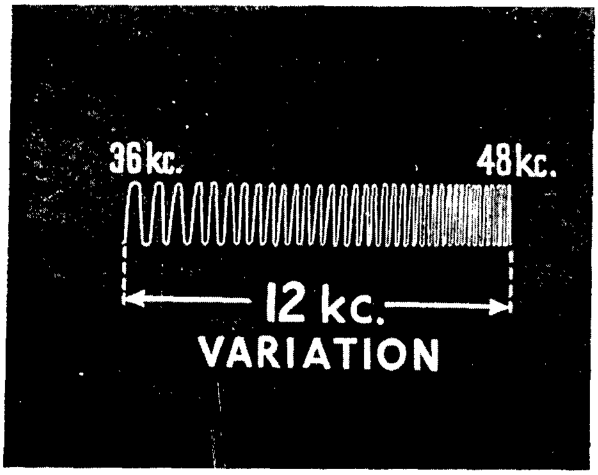


FIGURE 30. All such cycles begin with a maximum signal frequency of 48 kc and end with a minimum of 36 kc, a total variation of 12 kc.

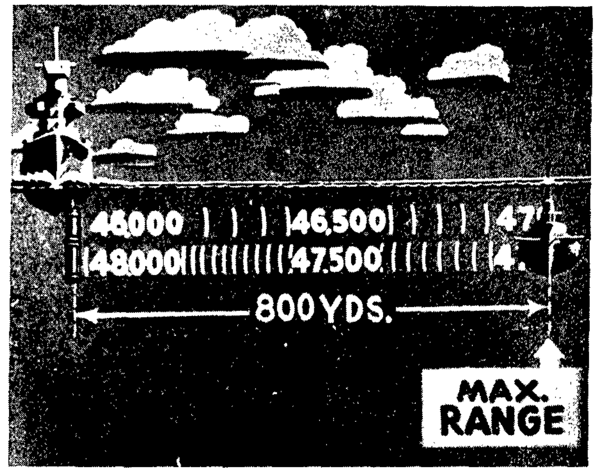


FIGURE 32. If the frequency is set to vary 12 kc in 6 sec, it varies just 2 kc in 1 sec as shown. This 2-kc variation is the maximum difference-frequency which can be accepted by the analyzer, and so sets a maximum range of 800 yd for a 6-sec modulation cycle.

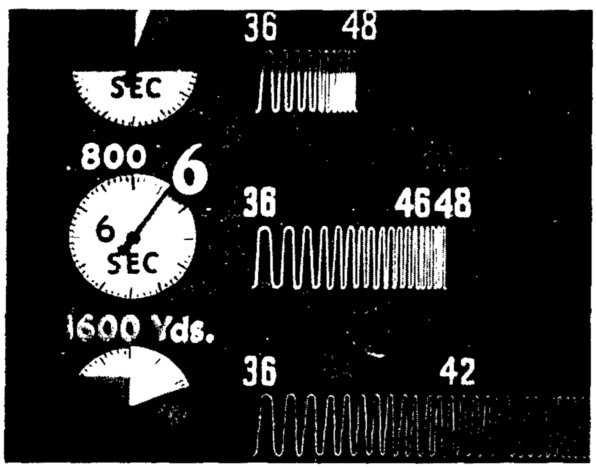


FIGURE 31. For example: at a range setting for a maximum of 800 yd, it requires 6 sec to complete the 12-kc modulation. A 12-kc variation in 6 sec means a 2-kc variation in 1 sec. One sec is the time required by sound to travel 1,600 yd in water, or to and from an 800-yd target.

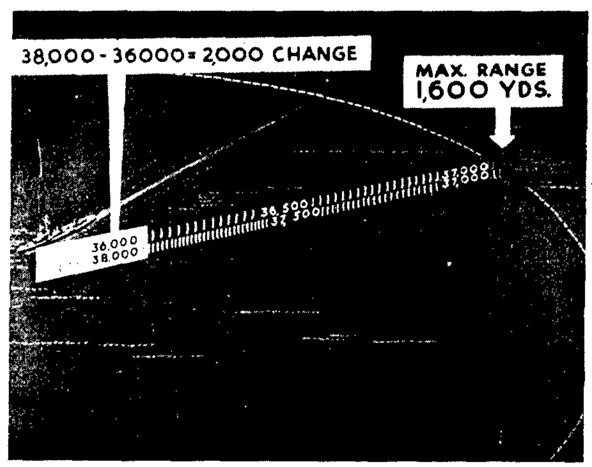


FIGURE 33. Now suppose we change the range-scale setting to a maximum of 1,600 yd. The frequency is then made to change 2 kc in 2 sec—the time required for sound to travel 3,200 yd, or to and from a 1,600-yd target.

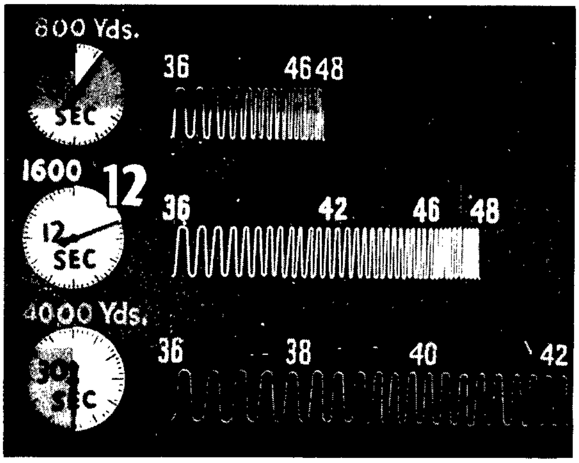


FIGURE 34. Twelve sec, therefore, are required for the 12-kc modulation when operating the 1,600-yd maximum range setting.

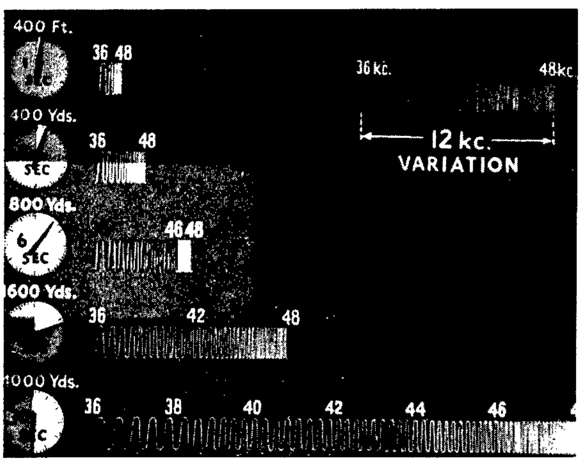


FIGURE 35. The same principle applies when operating at each of the other maximum range scale settings of 400 ft, 400 yd, or 4,000 yd. In every case, the rate of frequency change is such that there is a 2-kc change during the time required for sound to travel to and from the target at maximum range. If a target is at a distance *less* than the maximum range for any setting, the difference in frequency is proportionately less and is representative of that target's range.

1.4 HISTORICAL DEVELOPMENT OF FM SYSTEMS

As the preceding discussion should have indicated, it was the opinion of engineers of the University of California, Division of War Research [UCDWR] that f-m sound offered a number of advantages over the conventional types of echo-ranging gear utilizing pings or pulses, and, for this reason, all work of the FM Systems group at UCDWR was concentrated on the development of a system using f-m sound.

In attacking the problem, UCDWR engineers went beyond the basic echo-ranging requirements of locating a target rapidly at bearing and range to envision a device which would automatically delineate the outline of the target on the screen of the cathode-ray oscillograph. The realization of this ideal, of course, was long delayed, and many of the early systems were primarily concerned with working out a solution to the problem of using f-m sound for underwater detection without too much emphasis being placed upon the actual portrayal of the target.

The FM systems program was undertaken by UCDWR in the fall of 1941, shortly after the laboratory's organization. Arrangements were made with the Brush Development Company for production of the first system, designated the Echoscope system, in November of 1941. Soon after Brush began construction of the Echoscope, it became evident that linearity and stability of the *sawtooth-modulated oscillator* [SMO] would be a serious problem; consequently, an order was placed with the Bell Telephone Laboratories [BTL] for a sawtooth-modulated oscillator of improved design and of such a nature that it would be interchangeable in the Brush system with the Brush SMO. A similar order was placed with the Hewlett-Packard Company of Palo Alto, California.

FM systems being studied at this time were designated by the name Cobar (for continuous bearing and range). A number of experimental systems were assembled, each utilizing components of the Brush Echoscope in combination with the Bell Telephone Laboratories oscillator, the Hewlett-Packard Company oscillator, and various oscillators constructed at UCDWR and patterned after the Hewlett-Packard component. Development of FM systems (Cobar) continued for about a year and most of the attention was centered on basic problems of using f-m sound in echo-ranging and the development of a suitable receiver. While the Cobar systems afforded a high degree of range resolution, they

scanned range rather slowly. Attempts were made to utilize Cobar's high degree of range resolution in a fire-control modification of Cobar known as Subsight. (See Chapter 4, for details.)

The continuous nature of the information provided by Cobar combined with its high degree of range resolution and good signal-to-noise ratio, led to investigation[1] of its use in small-object (mine) detection. The capabilities of Cobar in this application were demonstrated to the Navy at Norfolk and created considerable interest as early as June 1943.

Early in the Cobar development (February 1942) a modification was attempted, under the designation Pribar, in which an attempt was made at a graphic portrayal of the target on the screen of the CRO. The Pribar systems used the Bell Telephone Laboratories supersonic prism as a fixed-position hydrophone, and scanned in bearing by phasing networks connecting the various elements of this multiunit hydrophone. Increased range-scanning speed was sought by injection into the receiver of a special 20-c modulation which was superimposed on the basic sawtooth frequency and which made it possible simultaneously to scan ranges from zero up to the maximum range for which the system was set. The Pribar system was rather complicated electronically, and, rather than attempt to describe it more fully here, reference is made to Chapter 4.

Cobar systems and their modifications, Subsight and Pribar, employed a narrow band-pass amplifier. It was realized, however, even during work with these early systems, that all range information necessary for the ideal portrayal was present in the system's first detector, if only some means could be devised for making it available in readily intelligible form.

In January 1943, a multichannel analyzer and electronic switch[2] were developed for use with the FM systems and made the information in the system's first detector available for intelligible presentation. Systems using the analyzer and multichannel switch were at first designated Fampas (for frequency and mechanically plotted area scan). The first Fampas unit portrayed range and bearing information in the form of a crude Cartesian coordinate plot on the CRO, but subsequent Fampas systems gave a PPI plot in which was presented a plan view of the area surrounding the echo-ranging vessel.

During work on Fampas-type sonar, the designation of the systems was changed to FM sonar and, under the name of FM Sonar Model 1 No. 1, a system was tested at New London, Connecticut, in which ranges on a submarine up to 3,200 yd were obtained.

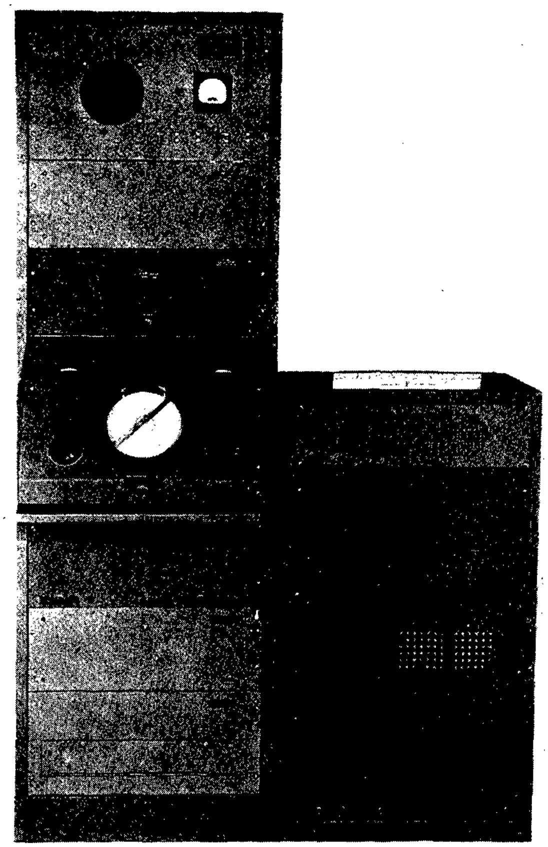


FIGURE 36. FM sonar equipment used in Ft. Pierce, Florida trials.

Until late fall of 1943, FM systems had been regarded primarily as an antisubmarine device. But with the relatively successful progress of antisubmarine warfare, the emphasis was changed to utilization of FM systems as a small-object detection device. In harmony with this new line of thought, FM Sonar Model 1 No. 1 was shipped to Fort Pierce, Florida, for trials

involving the detection of small objects in shallow water.

The interest which had been aroused in Navy circles by previously mentioned trials of Subsight as a mine detector at Norfolk brought a request for test of a system under actual battle

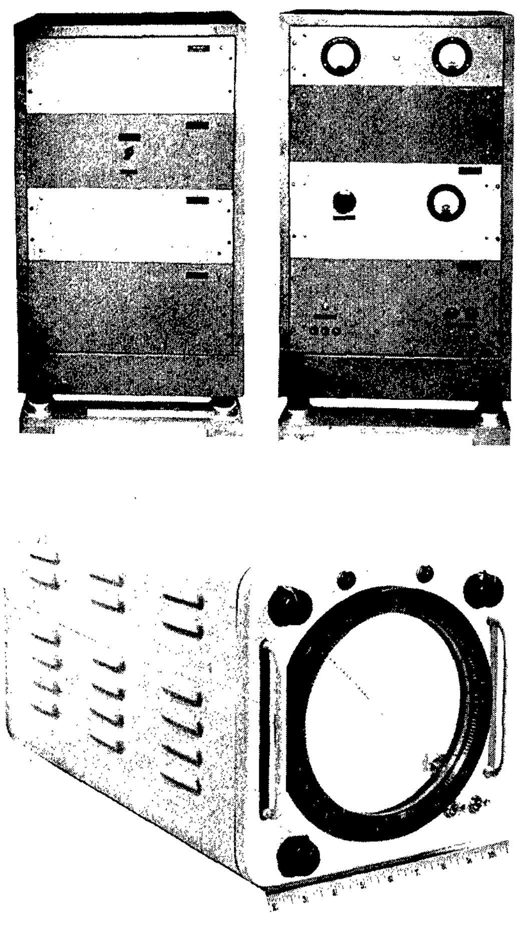


FIGURE 37. FM sonar equipment used in Mediterranean area trials.

conditions in the Mediterranean. UCDWR felt that the then current FM sonar would be suitable for this purpose, and accordingly a system known as Model 1 No. 1 (Modified) was taken to the Mediterranean by UCDWR engineers for trials under war conditions. The Mediterranean excursion showed that the system had good possibilities as a mine-detection device but brought out the fact that it was not, as yet, sufficiently rugged for operation under battle conditions.

In December 1943, a companion model to the Mediterranean unit was being tested and demonstrated at San Diego. A number of the submarine command saw these demonstrations and immediately became interested in FM sonar as a prosubmarine device.

Accordingly, an installation was made aboard the submarine S-34 and trials were run off the coast of San Diego. These initial investigations of the unit aboard the submarine indicated requirements for "repackaging" and certain installation improvements which were made in an installation on the submarine, *Spadefish*. The *Spadefish* installation was extensively demonstrated at Pearl Harbor under the auspices of ComSubPac, Admiral Charles A. Lockwood, Jr.

Results of these demonstrations witnessed by Admiral Lockwood and members of his staff were sufficiently good (particularly submarine navigation through simulated mine fields) to result in the institution of a program for the production and immediate installation of FM systems on 10 submarines to be operated in heavily mined Japanese waters. So urgent was the program that these 10 production models were installed only on submarines in for overhaul (rather than on new submarines) to assure the systems being used in war operations at the earliest possible date. During production of these units, the Navy designation, QLA sonar, replaced the older FM sonar.

In connection with the production program, UCDWR set up: (1) production consultation and testing program for the manufacturer, (2) a consulting service for the installing yards, and (3) a training program to orient veteran crews in the operation of QLA systems.

Nine QLA-equipped submarines completed some individual patrols and then it was decided to mass them all for the Japanese sea operation which is now a matter of history. Reports of this operation indicate that QLA, used as a navigational aid, was of prime importance in making this foray possible.

1.5 PERFORMANCE OF FM SYSTEMS [QLA]

Performance of QLA may be considered under two classifications: controlled tests and military operations.

1.5.1 Controlled Tests

PEARL HARBOR TRIALS

Each of the QLA installations was given a brief sea test offshore from the outfitting yard. Following this brief sea test, each submarine was dispatched to Pearl Harbor where more exhaustive trials were undertaken. The trials at Pearl Harbor served not only as a test of the equipment but also as a test of the sonar operators (who had been previously trained at UCDWR) as well as of the operational effectiveness of each submarine sonar team as a unit.

At Pearl Harbor, one of the tests undertaken was that of navigating through a simulated mine field. Dummy mine cases were used which approximated, in target strength, spherical moored mines of 36-in. diameter. On these targets an average certain range of 450 yd was experienced, and occasional ranges as high as 800 yd were obtained. Using FM system as a navigational aid, each of the vessels was able to negotiate the simulated mine field with apparent safety.

Additional tests were conducted in which the submarine used QLA to echo-range on a surface vessel. In these trials it was found that ranges were achieved with the FM system which were approximately equal to those achieved by the surface vessel in echo-ranging on the submarine with a pinging system.

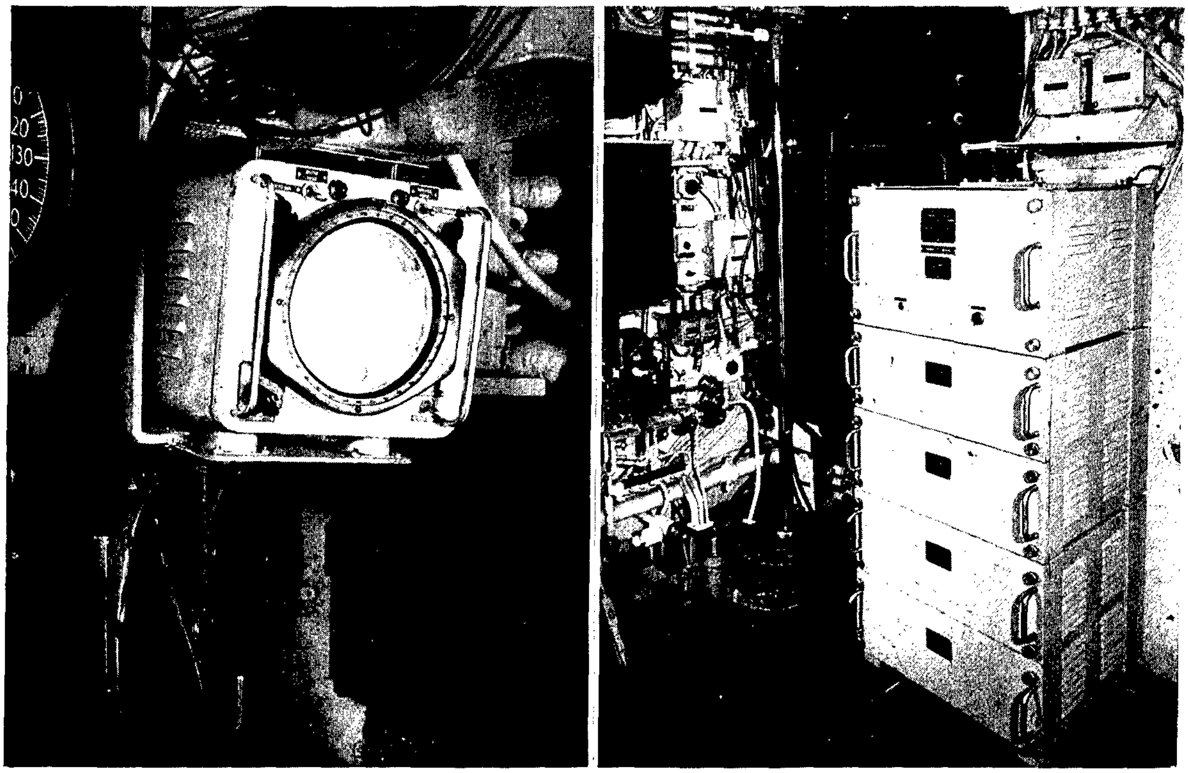


FIGURE 38. FM sonar equipment of type used on USS *Spadefish* installation.

SECURITY TESTS

Numerous listening tests were conducted off San Diego, Pearl Harbor, and at other places in an effort to evaluate the possibility that the FM signal of QLA could be heard in standard enemy, or friendly, listening gear. The listening tests indicated that it was sometimes possible to detect the QLA signal with standard listening gear, and that detection could always be accomplished by listening in the 36- to 48-kc operating band of QLA. Information then available through the Office of Naval Intelligence [ONI]

indicated 24 kc as the probable top frequency to which enemy gear was then sensitive. This knowledge, coupled with the results of the listening tests just described, tended to overcome the submariners' old aversion to the use of any kind of echo-ranging system in the presence of enemy listening gear.

Interference Tests

Investigations were also made into the possibility of interference arising under conditions in which FM and conventional pinging gear were operated simultaneously in the same echo-ranging area. These investigations showed that the FM signal caused no interference in pinging operations being conducted at frequencies below 36 kc. A ping signal above 36 kc is detectable with an FM system (as are second harmonics of some lower frequencies); but, because of its single-frequency character, it produces in the FM system only occasional chirps which do not seriously interfere with target identification.

Assistance in Evasive Operations

Tests were also conducted to determine the usefulness of FM gear in submarine evasive operations. Because the emphasis was then primarily on the use of the FM systems as a navigational aid, these tests were not so extensive as possible nor were the results obtained conclusive. However, results did tend to indicate that QLA gear would make it possible for a submarine to discover a sitting ship (as well as vessels under way) at ranges of 1,800 to 2,000 yd. Listening gear, of course, is unable to detect a sitting ship and this feature of QLA, therefore, has some tactical importance.

Report of the West Coast Fleet Sonar School

The following is an excerpt from a report of West Coast Fleet Sonar School use of QLA gear for other than training purposes.

> Listed below are . . . three incidents in which we have put the QLA Sonar to practical use. The results in each case were gratifying and are forwarded to you as of possible interest.
>
> 1. On 17 April, the USS *Torqua* equipped with QLA Sonar located the wreck of the S-37 which had broken away from her tow and sunk in shallow water about one mile off shore from Imperial Beach (California). The *Torqua* located the wreck after an unsuccessful two-day search by the PCS1441, equipped with QBF Sonar, and a Blimp equipped with MAD gear.
>
> 2. On 11 September, the USS *Ewing* (W137), equipped with QLA Sonar, located and buoyed the wreck of the USS PC815 which had sunk in 16 fathoms of water in latitude of 32-37-55 longitude 117-14-22. Contact was made on the first sweep and subsequent runs were made to definitely fix the position of the wreck. The services of the *Ewing* were requested by ComSoCalSec after failure of the salvage vessel, using a drag, and the *Eagle* 38, using QGB Sonar, to locate the wreck.
>
> 3. On 22 September (1945), the USS *Ewing* (W137), also located and buoyed the wreck of a fighter plane which had crashed and sunk near the channel in 55 fathoms of water. Salvage vessels, guided by buoy placed by *Ewing*, subsequently raised the plane.

Navigation of the Panama Canal

The following is an extract from letter dated 15 December 1945 from the commanding officer, USS *Flying Fish* (SS229):

> We used our QLA in the Panama Canal the other day. While we didn't have to, and I wouldn't particularly care to, I believe we could have made most of the transit with it alone as our navigational aid. We had a perfect picture of the channel in all the cuts and could spot buoys, sea walls, etc., with ease. And it seemed to work at 15 knots as well as it did at 5. Just below Gatun Locks, we could easily follow the channel 800 yards ahead, and the operator could tell me that we were about 15 yards to the left of the center of the channel. We also tried it in the lock—but got nothing—too many reverberations, I guess. The surface was usually just rippled and, of course, there were no swells.

1.5.2 Military Operations

The ultimate test of any echo-ranging system, of course, is its use under battle conditions. There have been a number of instances in which QLA and its forerunner, FM sonar, have been used in battle areas and it is the purpose of this section to indicate in a general way the tactical values of the equipment.

Mediterranean Area

First tests of an FM system in a battle area were undertaken at the instance of ComServRon Five, Norfolk, Virginia. The tests were conducted in the harbors at Palermo, Sicily, and Salerno, Italy, in June and July of 1944, with a

system known as FM Sonar Model 1 No. 1 (Modified). The following excerpts from the official report of ComServRon Five to Chief of Bureau of Ships indicate the type of results achieved with this system.

In the Gulf of Salerno, four Mark VI Drill Mines were laid over a mud bottom of the following depths: 85 fathoms, 79 fathoms, 30 fathoms, and 9 fathoms. These mines were detected at initial ranges varying from 220 to 400 yards. (Note: In all instances where initial ranges have been cited in this memorandum, contact with the objects was maintained down to 50 yards, which is the minimum range available on subject equipment.) [Subsequent systems utilized range scales which make it possible to bring targets within 75 feet, if desired.] One run was made at 5 knots and all other runs were made at 8½ knots. A light breeze prevailed; the sea was calm, temperature 80 degrees; injection, 77 degrees.

In the Gulf of Palermo, Mark VI Drill Mines with D-4 floats, Mark 23 obstructors, and type-three dan buoys were detected by the subject equipment at initial ranges varying from 125 to 390 yards, respectively. The mines and obstructors were moored 15 feet below the surface in 150 feet of water over a mud bottom in the Gulf of Palermo. The sea was smooth, temperature 90 degrees, injection 68 degrees. The afternoon effect decreased ranges. The best result obtained under the foregoing conditions was the detection of an obstructor at 325 yards. . . .

The official report of ComServRon Five explains the short ranges obtained in these tests, as being due to adverse thermal conditions, by going on to state:

During operations in the Gulf of Palermo, ASW vessels operating with a tame Italian submarine in an adjacent area over a period of four days obtained but one contact on a submarine at a range of 200 yards. No other contacts were made despite the fact that approximately eight ASW vessels were attempting to make practice runs on the submarine, which was towing a buoy and was ejecting markers. During the runs made in the Gulf of Salerno, an accompanying vessel equipped with a bathythermograph informed us that the bathythermograph reading indicated that 300 yards was the maximum range of the day. On one of our runs in that area, made immediately after receiving the foregoing information, contact was had (with FM Sonar) at 400 yards on a Mark VI Drill Mine.

TUNNY Patrol Report

The following brief summary gives the essence of the submarine *Tunny's* initial experience with FM gear: the first day, on entering the suspected area, she spotted one mine while submerged, and two other mines while on the surface, and commented that the navigation, the weather, and the FM gear were all perfect. The following day, in the course of 5½ hr while submerged in the depth of 100 to 150 ft, she made definite solid FM contact with 219 mines at maximum ranges up to 400 ft. This report was so extraordinary that the *Tunny* was asked to amplify it, and the suggestion was made that the contacts were oil drums from a shipwreck which had recently occurred in the vicinity. The full answer disposed of any doubts as to the validity of the contacts. They were uniformly spaced, in regular lines, and contacts were observed simultaneously on both sides of the submarine. Contacts dead ahead disappeared at a range of 100 ft as the submarine ran under the mines. The field was new and in an area reported by ONI as probably clear.

The Sea of Japan

In the early summer of 1945, nine submarines equipped with QLA gear were assembled at a point in the Pacific in preparation for a daring entry into the mined waters of the Japanese sea. All but one of these vessels obtained contacts on mines during their passage into the Sea of Japan, and all nine submarines were able to avoid the mines safely with the aid of the information obtained from the QLA equipment.

In addition to making this mission possible, the information provided by the FM systems had a further value: later comparison of the plots of the mine contacts obtained by these submarines permitted the preparation of a reasonably detailed chart showing the character and location of the mine field. After the end of hostilities these charts were found to be in good agreement with those of the Japanese admiralty.

Other QLA-equipped submarines made subsequent excursions into the Sea of Japan in the same manner.

Offshore Bombardment

Two submarines with QLA installations were concerned during the later stages of the war with the job of investigating offshore conditions on the eastern side of one of the islands of Japan. These boats plotted submerged targets in the area, and assisted in the extensive

offshore bombardment which was associated with the activities of the Third Fleet. The following brief excerpt from the patrol report of the submarine *Tinosa* is typical of this type of operation:

A scale reproduction of the island of Truk and reefs to the westward was made, and fixed on the DRT in the conning tower. Fox Mike (now QLA) Sonar presented a perfect PPI picture of the reefs. The fathometer was manned continuously. These three considerations provided perfect navigation 400 feet off the 10-fathom curve, and about 500 yards from the beach; provided an accurate plot of our maneuvers; gave excellent range and deflection to the gun on the nearly invisible target; and left SJ Radar free for spotting and sweeping. The quality of the fire control and navigation by this system was very gratifying.

Admiral Lockwood on QLA

Reactions of the submarine forces to FM systems can best be summarized, perhaps, by brief excerpts from two letters received by Director, UCDWR, from Admiral Charles A. Lockwood, Jr., Commander Submarine Forces, United States Pacific Fleet, as follows.

No doubt you have heard . . . of the tremendous success obtained by the (QLA Sonar) boats in the Japan Sea during the first sweep on which we had pinned such high hopes.

And from a second letter:

Five QLA's have run the gauntlet since the *Hellcat* operation (initial excursion into the Japan Sea, mentioned immediately above). The USS *Sennett* recently returned from a successful patrol with four ships sunk. She located mines at 800 yards and ran through two double rows of them.

1.6 QLA RÉSUMÉ

The device known, as of the date of this report, as QLA-1 sonar does not represent the ultimate in FM techniques or possibilities, but, rather, a stage in the FM systems development, tempered by expediency and the need for production of a device which would be of assistance during the recent war under particular and peculiar circumstances. It is, therefore, the purpose of the following paragraphs to survey briefly the present status of the FM systems development, and to indicate the general trend of proposed investigation and developmental work.

1.6.1 QLA-1, the Present FM System

Following the previously mentioned tests of an FM system (XQLA Serial No. 1) on the submarine *Spadefish* at Pearl Harbor, a production program was initiated in which UCDWR undertook to build five units known as XQLA Serial No. 2 through 6. At the same time a contract was placed with the Electrical Research Products Division of Western Electric for an additional five units known as XQLA Serial No. 7 through 11.

A second order was placed with Electrical Research Products Division of Western Electric for 12 units designated QLA Nos. 12 through 23. All the foregoing 22 systems (except QLA No. 21) saw service on submarines during the war.

A third order for 25 units was placed with Electrical Research Products Division of Western Electric to be known as QLA-1 Nos. 24 through 48. While these 25 units were under construction, the war with Japan ended. Of the 25 units, two were installed on submarines, two on mine sweepers, two were sent to New London for training purposes, and one was sent to the West Coast Fleet Sonar School (together with QLA 21) while the remaining 18 units await assignment as of the date of this report. The following evaluation of present systems deals with these 47 units.

Advantages of QLA-1

Ease of Manufacture. When the production program was undertaken, representatives of various commercial electronic manufacturers were invited to examine a system built by UCDWR with a view to determining its manufacturability. Among these were representatives of RCA, General Electric, and Western Electric. All expressed the belief that the type of construction would lend itself well to line production and expressed satisfaction with the individual components of the system. Western Electric's experience in the actual manufacture of some 50 units proved this to be true. As soon as they were provided with manufacturing specifications, production went ahead without delay, and they were able to meet all the deadlines on which they had agreed.

Ease of Maintenance. QLA gear is more complicated and, therefore, the maintenance problem is of slightly greater magnitude than is the case with prewar pinging gear. However, it is no more difficult to maintain than any other system using the advanced electronic techniques which have become so important to every branch of our military establishment during World War II. Experience with FM systems in the military installations previously detailed showed a very small amount of service trouble.

Technical Advantages. In addition to the two important advantages cited above, there are additional technical advantages which may be summarized briefly as follows.

Previously mentioned in this chapter were the advantages of (1) ability to scan rapidly and automatically in both bearing and range, (2) simultaneous portrayal of several targets, (3) ease of maintaining contact, (4) determination of target character, (5) availability of tactical information, (6) averaging of echoes, (7) relative immunity from countermeasures, (8) high signal-to-noise ratio, (9) small-object detection, (10) definition at extremely short ranges, (11) two-sense perception (eye and ear) which reinforce each other, and (12) modified security afforded by operating frequency and ability to scan a limited sector.

Two further technical advantages arise from the automatic threshold control which limits reverberation interference and form the capacity of the system for pulse-duration discrimination. These two features of the equipment are discussed in detail under the heading "Analyzer" in Chapters 3 and 5.

DISADVANTAGES

These may be briefly summarized to include: range inaccuracies arising from doppler, lost time, mechanical scan, possible crosstalk in high-speed installation soundhead domes, variation of effective pulse length with changes in maximum range settings, and signal attenuation due to operating frequency.

1.6.2 Trend of Future Development

In Chapter 8 of this report the trend of proposed future developments is treated in considerable detail. Reference is made to that chapter for more complete explanation of points covered herein. Research and development have been continuing since the end of the war with Japan so that some work on proposed developments has already been undertaken.

One of these, the problem of eliminating lost time, has already been solved. Lost time in QLA equipment is that time just after flyback in the modulation period, during which the sound field must be reestablished and which corresponds in duration to the round-trip time of sound to and from the target. At most, this lost time represents one-sixth of the modulation period. The elimination of lost time has already been achieved in the laboratory, but has not yet been incorporated in any production unit of QLA.

Investigations are also already under way on the problems of true-bearing addition to indication and elimination of range error arising from doppler. Increased range resolution has also been attacked from the angle of reducing the width of filters used to analyze the incoming signal which at present do not approach a parameter which yields the maximum possible utilization of the FM principle. While considerable progress has been made on these three problems as of the date of this report, the final answer to any of them is not available.

There is still a third class of possibilities for future development which is under consideration but on which no developmental work has as yet been actively undertaken. This class of possibilities includes: improvement of the system's ability in the field of torpedo detection, provision for increased bearing resolution, an improved range and bearing cursor, fire-control provision (probably by an adaptation of the Subsight principle to QLA), depth and/or elevation determination, plotting board indication, and modification of soundhead to simplify scanning.

In this third class should also be included the problem of range-rate indication. Current investigations into the matter of doppler correction, however, tend to indicate that range-rate indication may be solved with the solving of doppler correction problem.

An FM system incorporating these proposed developments would offer a complete catalog of information on the static and dynamic characteristics of any type of target.

Chapter 2

FREQUENCY-MODULATED ECHO RANGING

2.1 PRINCIPLES

2.1.1 Aspects in Common with Other Echo-Ranging Techniques

In common with other sonar echo-ranging systems, the frequency-modulated echo-ranging system [FM] transmits a sound signal in confined directions, awaits the returned echo or reflected sound from a target, and presents a sensible change to the operator at the time of predetermined directional reception. Thus, the presence of a target is detected by light and/or sound stimulation to the operator. Its bearing is assigned according to the confined beam sensitivity of the receiving hydrophone, and its range is measured by the elapsed time

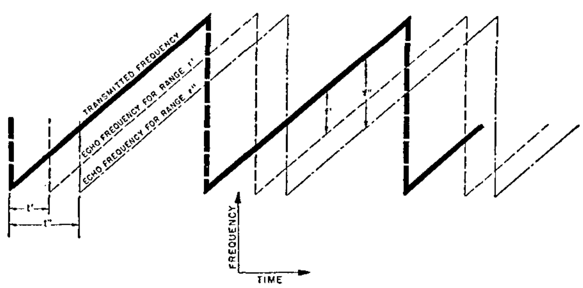


FIGURE 1. Constant difference frequencies, f' and f'', exist between the transmission frequency and the echo frequencies for targets at ranges $r' = ct'/2$ and $r'' = ct''/2$.

between transmission of the sound to and reception from the target by assuming the velocity of propagation to be a known constant in the medium.

Different systems are thus defined and named in terms of the peculiar means employed to bring about the detection observation and the range and bearing measurements. Frequency-modulated echo ranging is characterized in its detection observation by a change in energy intensity at a particular frequency, as bearing and range are scanned, and presents the intelligence both to the operator's ear (through a common loudspeaker) and to the operator's eye (by means of narrow electric filters feeding a cathode-ray tube) in a manner to excite the senses in terms of amplitude and frequency. If continuous contact is desired, FM echo-ranging has the capacity to present a nearly continuous indication which varies in amplitude and frequency to a degree limited only by the medium and equipment which, of course, are not ideal.

The range measurement, by elapsed time, is determined by observing accurately the fre-

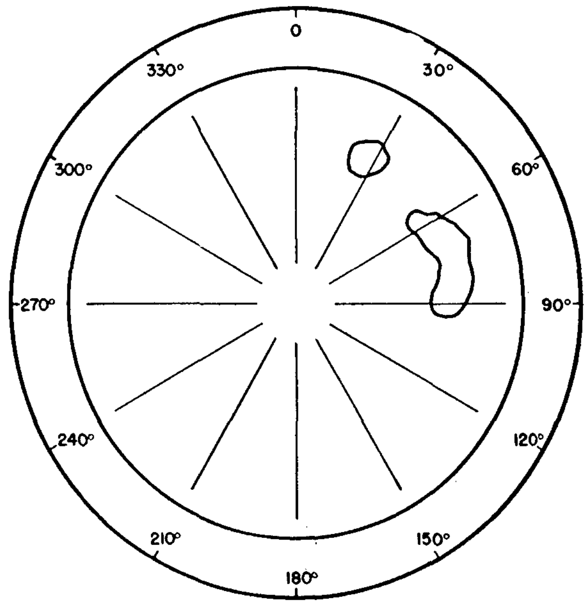


FIGURE 2. The PPI or plan position indication of target position in range and bearing, enables the operator quickly to survey and follow movements of target. The size of the spot usually is determined by widths of analyzing apparatus, such as beam width and filter widths.

quency of the returning echo with relation to the frequency of the signal being emitted, under conditions in which both are changing in a regular and known way with time. This characteristic of changing frequency with time has been used to derive the name, frequency-modulated sonar. Figure 1 illustrates how a fixed frequency difference f may be associated with a fixed time of transit t to and from the target at range $r = ct/2$. Here c represents the constant sound velocity.

Target bearings are associated directly with the axis of the main lobe of the receiving transducer. In the case of phased response in a split soundhead such as is used in *bearing deviation indicator* [BDI], the bearing may be associated with the direction of the previously measured null response. Such bearings of hydrophone positions during a scanning operation have been portrayed on the circular screen of a cathode-ray tube in *plan position indicator* [PPI] with great advantage as compared to a simple compass card with pointer. Such relative bearing positions with FM sonar of the QLA type are illustrated in Figure 2, showing relative plan location of various reflecting objects in near-by water. In this case range (or frequency difference) information is presented as spot displacement from center of the screen.

The problem of continuous contact with target, or insurance against loss of contact between pings by reason of bearing deviation between projector bearing and target bearing, has its counterpart in FM systems. However, because of the continuous nature of the FM output and simultaneous echo analysis, loss of contact by bearing deviation should be reduced to a minimum for a given speed of bearing scan.

2.1.2 Factors Limiting Range of Detection

In general one may say that an echo or signal is detectable if its intensity is at least a certain number of decibels greater than the neighboring background level. This minimum detectable ratio of signal to background is called recognition differential ∂ and in general depends upon characteristics of the signal, the background, and the apparatus of reception and presentation. It may be either a positive or negative value. In general terms one speaks of two recognition differentials, corresponding to the two background types, reverberation and noise. An algebraic form of the above statement is

$$2H_{\max} = S + T - (\partial + \beta) \tag{1}$$

where:

$2H_{\max}$ = maximum two-way transmission loss,
S = transmitted signal strength,
T = target strength,
∂ = recognition differential,
β = background level, summation of reverberation and noise.

Equation (1) would presumably determine a maximum attenuation at which the target in question is just detectable. Since $2H_{\max}$ is a monotonic increasing function of range, the maximum range of detection may be expressed in terms of this factor. In the following paragraphs, the various items which influence or determine the maximum detection range are discussed with particular reference to frequency-modulated echo ranging.

Power Output (S) vs Frequency

When β_n (background noise level) is greater than β_r (background reverberation level) an increase in S (the output power) would increase the ratio T/β_n, at a given range, or increase the maximum range of detection for a given target. In other words, under the above conditions the maximum tolerable two-way transmission loss $2H_{\max}$ at which target detection is still possible may be increased.

However, if β_r is already greater than β_n, an increase in the output power S would *not* increase the maximum range of detection since β_r is proportional to S. In FM systems, since the frequency band used is an appreciable part of an octave, it is not easy to keep the power output constant over the band, nor would such a constant power output be perfectly desirable because of transmission loss variation with frequency. Ignoring this latter fact, however, it seems necessary to flatten the driver amplifier-transducer response in order to approach constant echo level. The importance of this constant output level becomes more evident when recognition is discussed in later paragraphs.

As an example of what has been achieved in the direction of constant power output, one observes from Figure 10, Chapter 5 that the 36-kc output of QLA-1 is some 4 or 5 db below the 42-kc output. Such a deviation is tolerable if other effects are not in the same direction. The maximum pressure output of present QLA systems is about 106 to 108 db above 1 dyne per sq cm at 1 yd from the projector. This maximum pressure is some 10 db lower than might be possible with continuous signals from a flat 14-in. projector. Therefore, if in future work it is found that noise is a limiting factor in FM operations, there would be some room for im-

provement in the direction of increasing power by increasing the size of the radiating face and by maintaining the same transducer beam patterns. This method, however, is of doubtful value since equipment bulk is likely to limit such an attempt.

Transmission Strength vs Frequency

When one observes the indicated signal from a small target at constant range with FM sonar, particularly with Delta Cobar, the fluctuation in the presented intensity is usually a slowly changing function of the emitted frequency although the function itself may exhibit occasional sharp minima. In general this phenomenon may be associated with the transmission loss which depends solely on frequency; but for particular image conditions, changes may occur over wide limits due to other factors. Transmission losses in ocean water are conveniently described by assigning the sound intensity change with range to inverse square divergence plus other losses. The former is expressed in decibels by 20 log r so that the total transmission loss H referred to intensity at unit distance from a source is

$$H = 20 \log r + A \tag{2}$$

where r is range in yards and A is the total anomalous loss which may be the result of scattering, refraction of beam, or other undetermined causes.

Under good transmission or mixed-layer thermal conditions, one may express the average two-way transmission anomaly in decibels, by $2A = 2ar$ in which the absorption coefficient a is given approximately by $a = 3.3 \times 10^{-9}F^{1.4}$ db per yd where F is in cycles per second and r is in yards.[3] Thus in the example of present QLA equipment where the frequency varies from $F = 36$ kc to $F = 48$ kc, one may expect absorption coefficients to vary from 8 to 12 db per kyd. And, therefore, at a 1,000-yd range the signal may vary by as much as 8 db from change in average attenuation coefficient alone.

For image effects (see Figure 3) one has the formula for two-way path difference between direct and surface-reflected sound:

$$2\,(\Delta r) - \frac{4h_1\,h_2}{r} \tag{3}$$

where h_1 and h_2 are transducer and target depths respectively, r the range, and Δr the range difference between the direct and reflected sound paths. In terms of the phase angle difference $\delta\phi$, one then finds

$$\delta\phi = \frac{2\pi}{\lambda} \cdot \frac{4h_1\,h_2}{r} \tag{4}$$

where λ is the wavelength for a given frequency F and velocity c. For two different frequencies, F_1 and F_2, one may subtract the phase angle differences:

$$\begin{aligned}\delta\phi_2 - \delta\phi_1 &= \frac{8\pi h_1\,h_2}{r}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\\ &= \frac{8\pi h_1\,h_2}{rc}\,(F_2 - F_1)\end{aligned} \tag{5}$$

where c is the velocity of sound.

If one lets this difference in phase equal π, and solves for range, the maximum range r_m for strong interference fluctuations is expressed:

$$r_m = \frac{8h_1\,h_2}{c}\,(F_2 - F_1). \tag{6}$$

For example, if $h_1 \times h_2 = 100$ sq yd with $F_2 = 48$ and $F_1 = 36$ kc,

$$\begin{aligned}r_m &= \frac{8 \times 12 \times 100}{1.6}\\ &= 6000 \text{ yd.}\end{aligned}$$

At this range the frequency for maximum intensity is 36 kc and for minimum 48 kc. Corresponding to phase delays in path of 3π and 4π, respectively, minima occur at larger ranges, but maximum and minimum do not both occur at any longer range. At shorter ranges, there is more than one change from maximum to minimum signal intensity during a single-frequency modulation period. In this way large fluctuations in received intensity are easily accounted for, and must be expected in any FM system. Instead of being a disadvantage, however, this effect emphasizes the fact that FM systems are probably less limited by poor transmission than are single-frequency systems.

One other point should be made concerning transmission loss, a point which bears on the selection of operating frequencies. For some purposes, high frequencies prevent detection because of high attenuation while for others (at short ranges where divergence is more important) the high attenuation is not a disturb-

ing factor. The following formulas enable one to determine the range, r_f, at which frequency effects become more important than geometrical divergence. The total attenuation loss is $2a_t r$ and the divergence loss is 40 log r. When each of these is differentiated with respect to range and equated, and solved for r, one obtains:

$$r_f = \frac{8.7}{a_t} \tag{7}$$

where a_t is given in decibels per yard. For example, if it is desired to operate at a 2,000-yd range, the maximum attenuation coefficient to insure less loss by attenuation than by divergence at that range is $a_t = 4.3$ db per kyd, which corresponds to frequencies near 24 kc. On the other hand if ranges of only 500 yd are needed, attenuations of 17 db per kyd would be safe, and thus a frequency around 60 kc could be used. Further, if short-range bottom scanning at 300 ft maximum depth is the problem, 200 kc would not be too high. Here it should be kept in mind that r_f is not maximum detection range in any sense but is simply a first estimate of range at which attenuation, and thus frequency, begin to become dominating factors. Figures 4 and 5 show typical relations between r_f and a_t, and between a and F.

Transmission losses occurring in thermal patterns other than mixed layers have been investigated by UCDWR, but the results are not simple to describe. Suffice it to say that refraction of a highly directional pattern apparently produces absorption losses which rapidly become the dominant factor in transmission anomaly as the angle of refraction increases. At 24 kc, rates of change of anomaly with range have been observed to vary from 4 to 14 db per kyd as the downward refraction becomes more pronounced.[4] Such an effect, however, should show no frequency dependence.

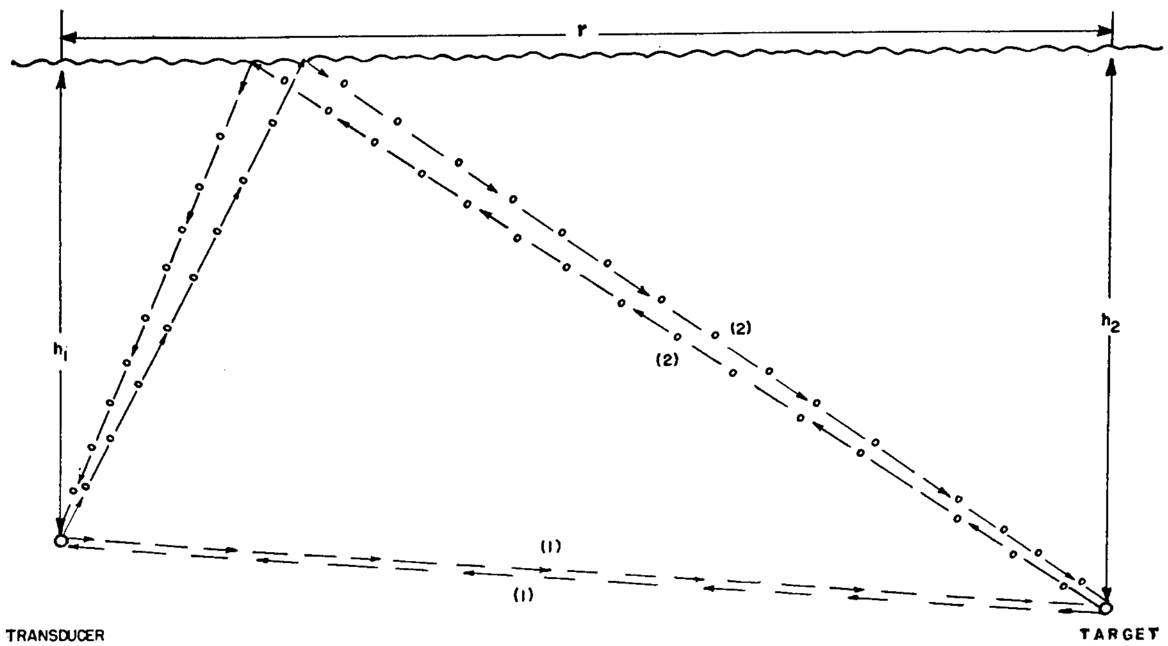


FIGURE 3. Two path transmission and reflection (1) and (2) with phase reversal at surface, cause phase interference fluctuations in received intensity.

TARGET STRENGTH VS FREQUENCY

In equation (1), the term T, called target strength, is defined in decibels as the ratio of the effective diameter d of the target in question to that of a sphere 4 units in diameter, usually 4 yd. Thus a sphere of 1-yd diameter is spoken of as having a target strength of -12 db since $20 \log d/4 = -12$ for $d = 1$. This formula,

$$T = 20 \log \frac{d}{4}, \tag{8}$$

is the result of the derivation by Willis[5] which states that the sound pressure X reflected from a sphere of radius a at distance r when placed in a uniform field C is given by

$$X = C\frac{a}{2r}. \tag{9}$$

Thus, the diminution of intensity of the im-

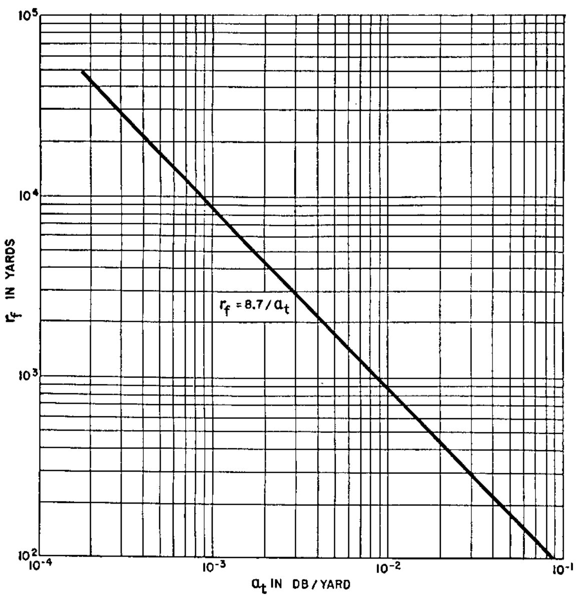


FIGURE 4. There is an inverse relationship between attenuation coefficient, a_t, and critical range, r_f, at which rate of divergence loss equals rate of attenuation loss.

pinging sound C to that returned, X can be expressed in decibels as

$$\begin{aligned} 20 \log \frac{a}{2r} &= 20 \log \frac{a}{2} - 20 \log r \\ &= T - 20 \log r. \end{aligned} \tag{10}$$

Accordingly, the target strength T simply describes by how much the reflected intensity is increased above that determined by spherical divergence. Absorption and scattering in the medium are here neglected.

A spherical target is nondirectional and its strength is approximately independent of frequency. However, if one examines targets with plane surfaces, strong frequency effects arise. For example, a smooth disk of radius a_d is equivalent to a sphere of radius a_s:

$$a_s = \frac{2\pi}{\lambda} a_d^2 \cos\alpha \left[\frac{2J_1(\varphi)}{\varphi}\right], \tag{11}$$

in which $\varphi = 2a_d(2\pi/\lambda) \sin\alpha$ is the argument of the Bessel function J_1 of the first order, where λ is wavelength of sound reflected and α is angle which the normal to surface makes with direction of incident or reflected sound.

A numerical example shows the importance of the frequency effects of this expression. Let $\alpha = 0$ then $a_s = (2\pi/\lambda)a_d^2$, and accordingly a disk of 6-in. radius at wavelength of 1⅔ in. (36 kc) is as strong as a sphere of 136-in. radius for which $T = 5.6$ db, and at $\lambda = 1\frac{1}{4}$ in. (48 kc) is equivalent to a 181-in. radius sphere for which $T = 8$ db. Thus, on the axis normal to the face of the disk a 2.4-db frequency variation can be expected between 36 to 48 kc; this is not too severe for a dynamic range > 10 db. However, if one echo ranges off axis of a plane smooth surface, the directivity function, $2J_1(\varphi)/\varphi$, produces much greater fluctuations in target strength with frequency. For example, at 2 de-

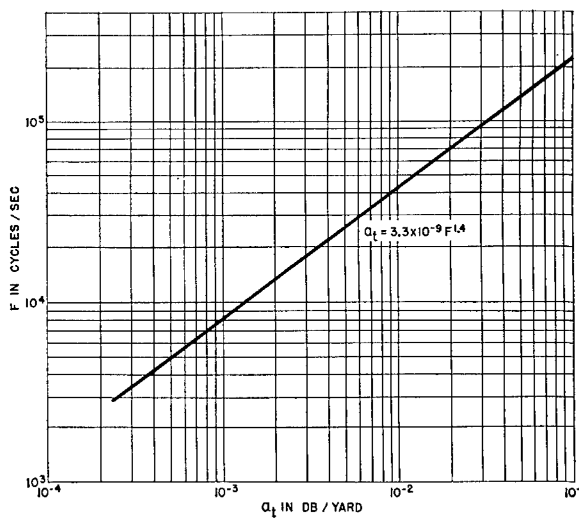


FIGURE 5. Average attenuation coefficient a_t increases approximately as 1.4 power of frequency F.

grees off axis, the 36-kc target strength drops to 2.7 db and the 48-kc strength to 2.6 db; and at 3 degrees the respective values are -1.6 db and -7.8 db; so that on-axis the 36-kc strength would be 2.4 db lower than the 48-kc strength, but at 3 degrees off-axis it would be 6.2 db greater. From such an example it is easy to realize that echo levels fluctuate greatly as the frequency sweeps over wide limits. Figure 6 is a plot of the target strengths of the above ex-

ample of a 6-in. disk, as the angle α of incidence and reflection is changed.

Attempts to measure strengths of complex targets at frequencies other than 24 kc have not been extensive enough to show definite conclusions. However, great fluctuations in the existing measurements, and trends in measurements

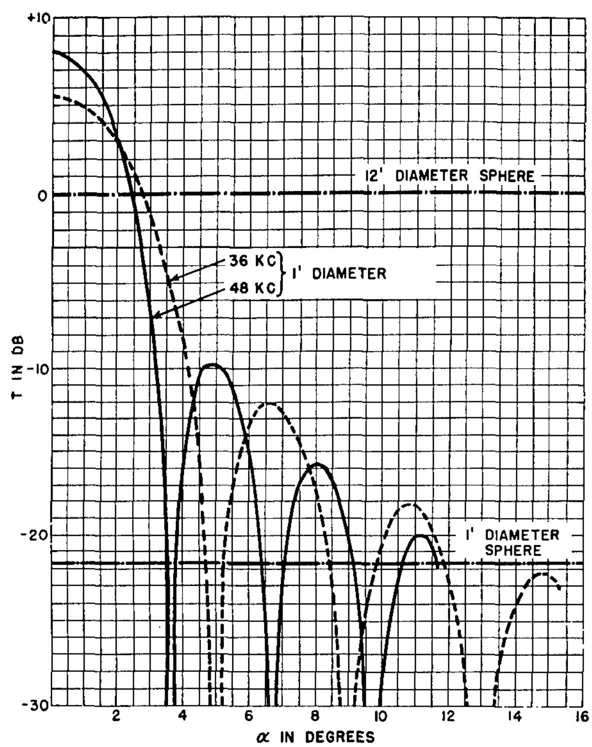


FIGURE 6. The target strength of a flat 1-ft diameter disk shows rapid change with angle of incidence and reflection.

which indicate increase of target strength with range and frequency, tend to support the view that flat surfaces have strong frequency and aspect dependencies.

NOISE VS FREQUENCY

If the background level β in a sonar system is noise (i.e., receiver output variations independent of the presence of the projected and reflected sound energy) it may be usefully described in terms of single-frequency sound pressure at the hydrophone which would be necessary to present a similar intensity of indication to the observer. If this information is available, then equation (1) can be used to estimate maximum range of contact as limited by such noise background. Such noise background may originate in the water in which the hydrophone is immersed or in the electronic equipment itself.

Good electronic sonar receiver systems would be capable of indicating background noise levels existing in the water. In general, one should be concerned with internal electronic system noises to the extent that they must be reduced until the above condition for good receivers is met for the lowest anticipated water noise level. Accordingly, in these paragraphs only water noises are considered. Furthermore, water noises are of two types: (1) nondirectional noise from miscellaneous causes (such as the breaking of surface waves) and (2) directional noises originating at definite locations (such as at the screws of a ship). Each of these types of noise has certain frequency characteristics which need to be known. In this instance, the average amplitude description of this noise as a function of frequency is important. In some cases the transient or pulse character of the noise is important.

In order to discriminate against noise, two devices are important in sonar systems, and both are used in FM echo ranging. First, the directional properties of the receiving transducer, which are primarily used to define echo bearing, also aid in reducing the effective noise level of nondirectional noises. This property of directional transducers is described by a single number called directivity index, and may be defined as 10 times the logarithm of the ratio of the observed response to nondirectional noise to that response which a nondirectional unit would give if its sensitivity were the same as that of the directional axial sensitivity of the directional transducer.

Some investigations[6] of common transducers of not too high directivity have shown that the directivity index can easily be expressed as

$$D = 20 \log \theta - 45.9 \text{ db} \qquad (12)$$

where θ is the total angular beam width in degrees, measured at the points 3 db below maximum response. For example, the present QLA hydrophone beam pattern (Figure 9, Chapter 5) shows a width of about 14 degrees at 42 kc. This hydrophone has a directivity index of -23 db and can discriminate against

nondirectional noise to the extent that it has a 23-db advantage over a nondirectional hydrophone. In FM systems, the directivity index changes throughout the frequency sweep since beam patterns become sharper for higher frequencies. Thus, since 20 log 48/36 = 2.4 db (approximate for a flat-faced transducer), the directivity index may be expected to change from about −22 db at 36 kc to −24 db at 48 kc. However, since there is some evidence to show that random noise pressures decrease about 6 db per octave, it is possible that for nondirectional noise limitations the 48-kc portion of the sweep has about a 5-db advantage over the discrimination against nondirectional noise at 36 kc.

Hydrophone directivity is not very successful in reducing the effective background level associated with a noisy target; e.g., a submarine echo ranging on a fast carrier finds the noise and the echo coming from about the same direction.

In such a case a nondirectional hydrophone would do as well. Directional hydrophones, however, do discriminate against directional noises that do not have origins in the beam axis direction. In this case the discrimination is measured directly by the beam-pattern response as a function of angle off the beam axis. For example, a noisy ship nearby would have its masking effect reduced by about 20 db if it were as much as 15 degrees off the beam axis.

The other device used for noise discrimination is that of the conventional band-pass filter, in which only those noise energies whose frequencies lie within a small band are permitted to reach the indicator. Consequently, the effective masking level of a given noise background bears a direct relationship to the bandwidth of the receiving apparatus. Thus, if two filters of 100- and 1,000-c bandwidths respectively are compared in a uniformly distributed noise background, the narrow filter gives 10 db extra discrimination over that offered by the wide filter. For this application noise levels are often expressed in terms of equivalent pressures for a 1-c pass band, and this is then called the spectrum level at each frequency.

In illustration of the influence of both directivity index and filter bandwidth on the effective noise background, the following hypothetical case is offered: Assume a state 2 sea which presents a spectrum noise level (decreasing 6 db per octave) of −30 and −33 db referred to 1 dyne per sq cm at 36 and 48 kc respectively.

It is desired to echo range at 3,000 yd on a fast carrier which has an equivalent spectrum output level at 1 yd of +35 and +32 db referred to 1 dyne per sq cm at 36 and 48 kc. At 2,000 yd, and 40 degrees off-target bearing is a small boat which has an equivalent spectrum output level of +20 and +17 db referred to 1 dyne per sq cm at 1 yd for 36 and 48 kc, respectively. The problem is: What echo level equals the equivalent noise conditions set forth above, if the receiver pass band is 100 c wide?

1. At 3,000-yd range, the target (fast carrier) noise levels would be −35 and −38 db, if it were not for attenuation of 8 and 12 db per kyd at 36 and 48 kc respectively, which brings the target noise levels down to −59 and −74 db at the terminal frequencies of the FM operating band.

2. Equivalent spectrum levels for the interfering small boat (2,000-yd range) would be −62 and −73 db except for influence of the directivity of the FM hydrophone which brings them down instead (at 40 degrees off bearing) to −92 and −98 db at 36 and 48 kc, respectively. The effect of the directivity index of the hydrophone brings the sea spectrum levels down to about −52 and −57 db referred to 1 dyne per sq cm in 1-c bands, but leaves it the principal noise. For a 100-c filter, 10 log 100 = 20 db; hence (because of the influence of the filter width) echo pressures from the 3,000-yd target of −32 and −37 db referred to 1 dyne per sq cm is equal to the noise background levels.

As a second illustration, assume the carrier to be at 1,000-yd range, the interfering small boat 15 degrees off target bearing at range of 500 yd, and the sea spectrum the same (−52 and −57 db at 36 and 48 kc, respectively). Under these new conditions target noise levels are now −33 and −40 db but spectrum levels of the interfering small boat have become −48 and −63 db so that they are higher than sea noise during part of the frequency modulation cycle. Target noise, however, has gone far above either of the other two masking noise sources.

After taking into consideration the 20-db advantage obtained with the 100-c filter width it becomes evident that echo pressures from the 1,000-yd target of −13 and −20 db referred to 1 dyne per sq cm are equal to the noise background established by noise of the target itself.

From these illustrations it can be seen that noise masking and analysis factors in FM systems can create a complex situation, because of the various frequency-dependent characteristics of noise sources, beam patterns, and attenuation in the water. This complexity may prove advantageous in practice since the operating frequency of an FM system is not confined to a single value which might possibly in a given set of conditions result in an unfavorable signal-to-noise ratio.

Reverberation vs Frequency

The previous discussion concerned noise as the predominating background. Here, under the subject of reverberation, a more complex situation is involved. Reverberation may be expressed as the sum of all echoes or reflections returning to the sonar hydrophone except that from the target. In pinging systems the volume of water from which reverberations can come at any instant is determined by the beam patterns of transducers and by the pulse length of the ping. The former determines the solid angular boundary of the active shell. The latter determines its thickness.

In continuous systems reverberation arrives from all ranges simultaneously. On the other hand, the effective level of reverberation β_r depends not only on directivity characteristics but also, as in noise considerations, upon the band-pass characteristics of the receiving-analyzing apparatus.

In general, the reverberations from the shortest range are of highest intensity and those from longest range, the lowest. Accordingly, the analyzing apparatus must first of all be able to discriminate against nearby reverberation, and to a lesser degree against reverberation from longer ranges. Since range in FM systems is determined by frequency difference of transmission and echo signals, discrimination against reverberation is accomplished in terms of definite frequency characteristics of the receiving filters and can be expressed in terms of range for the simple types of reverberation, namely, volume, bottom, and surface.

Let T_p be the period of FM sweep during which the frequency changes by F_p cycles per second. Accordingly, the rate of sweep is F_p/T_p and the frequency change f in time $(t = 2r/c)$, corresponding to range r is:

$$f = \frac{F_p}{T_p} t = \frac{F_p}{T_p} \frac{2r}{c}. \tag{13}$$

This defines the frequency f of the band-pass filter (i.e., midfrequency) which passes signals from this range (i.e., mid range). The width of the filter (δf) corresponds to a range width (δr) as given by

$$\delta f = \frac{F_p{}^2}{T_p} \frac{\delta r}{c}$$

or

$$\delta r = \frac{T_p c}{2F_p} \delta f = \frac{r}{f} \delta f. \tag{14}$$

The angular extent Ω of the active reverberation volume is given approximately by

$$4\pi\,\Omega = \frac{\theta^2}{16}\left(\frac{1}{57.3}\right)^2 = \frac{\theta^2}{5.2 \times 10^4}$$

so that the total active volume v would be

$$v = 4\pi r^2\,\Omega\,\delta r. \tag{15}$$

Here θ is the 3-db down point lobe width of the hydrophone pattern, for the case of circular symmetry about beam axis. For example, if $F_p = 12$ kc, $T_p = 2$ sec and $\delta f = 0.075$ kc, $f = 1$ kc, the reverberation shell thickness at range $r = 133$ yd would be $\delta r = 10$ yd, and its volume v would be approximately 4,000 cu yd. If the filter widths for each range are equal the volume increases as the square of the range or difference frequency, and so one would expect that the reverberation level for each filter would increase as 20 log r compared to the echo level from a spherical target. Hence, for a constant echo-to-reverberation ratio the successive filter widths should decrease inversely as the square of the frequency. If a 300-c filter gives a satisfactory echo to reverberation ratio at 200 yd, then at 400 yd a 75-c filter would be required,

and the 600-yd range filter should be only 33 c wide. Although such an inverse arrangement may not be compatible with range accuracy required, it at least serves to emphasize the need of narrow filters at long ranges if reverberation effects are to be suppressed.

Equation (14) expresses the width of the range annulus which activates the filter of width δf, and therefore defines the effective pulse length (τ_f), of FM sonar when compared to pinging systems.

$$\tau_f = \frac{2\delta r}{c} = \frac{T_p}{F_p}\delta f. \tag{16}$$

This method of determining effective pulse length in seconds may be used for rendering reverberation data obtained by pinging systems[7] valid for the purpose of FM predictions. (Pulse length is also used, in yards, as the active thickness, not the length of wave train.)

For example, under certain reverberation-limited conditions a target strength of -10 db is masked by reverberation at ranges beyond 200 yd for 100-msec pings using transducers of directivity index of -24. If in an FM system $T_p = 3$ sec, $F_p = 12$ kc, and $f = 75$ c, the equivalent pulse length would be about 19 msec or 15 yd. Accordingly, the FM reverberation level, for similar transducers would change by 10 log $19/100 = -7.2$ db. Thus a target strength of about -17 db would be detectable under similar conditions.

For an FM system employing transducers whose directivity patterns differ from those of the transducers with which the pinging measurements of reverberation have been made, it is necessary to evaluate and correct for the difference between reverberation indices which for wide-beam FM transmission are almost identical with the directivity index previously mentioned in this section in connection with the analysis of nondirectional noise.

It was only mentioned before that the discrimination characteristics of the electric filters could be described in terms of range and frequency for the simple types of reverberation. Now with equation (13) in which frequency f is proportional to range r and with equation (15), for active volume in volume reverberation, it is seen that the reverberation volume increases as the square of the range or frequency, but since the intensity of reverberation changes as $1/r^4$ for any single, small scatterer, it is seen that the total level from each range, i.e., at each difference frequency, changes as $1/r^2$. From this it is seen that reverberation of a 500-c difference frequency is 6 db higher than that of a 1,000-c frequency difference. Accordingly, the filter should show increased discrimination at the lower frequencies by 6 db per octave more than would be indicated by flat input. In practice, however, the sharpness of the filter near the cutoff points is determined by requirements for range accuracy and target definition, rather than by reverberation suppression considerations.

Some of the most serious of reverberation effects can be those of acoustic coupling between projector and hydrophone. These effects can be eliminated to a great extent by careful transducer design.

Ambiguity of Range Indication. Reverberation effects, in terms of strong targets at long ranges, may present problems in a practical FM echo-ranging system since continuous change of the frequency is not practicable and, instead, the frequency is changed in a cyclical saw-tooth-modulation pattern. Therefore on successive frequency sweeps, it is at least possible that ambiguity may occur in the range indication of targets at ranges r_a, as illustrated by the following equation:

$$r_a = \pm r + \frac{ncT_p}{2}, \tag{17}$$

where n is the first, second, third, etc., sweep after the initial one illustrated in Figure 7.

Such effects could become disturbing, especially when the FM system is used to detect small objects such as mines under conditions where much larger targets at long range may be encountered (such as an enemy submarine) and be mistaken for a small target at close range. Many ways may be devised for identifying such an ambiguous contact; for example, by navigational observations of range and bearing or change of echo level with indicated range. However, it may be desired to eliminate such

ambiguities as much as possible. This may be accomplished either by making r very small compared to r_a, i.e., by increasing the sweep period T_p or by making the range loss ($40 \log r_a + 2r_a a$) very large for r_a compared to that for a range r, by selection of a sufficiently high frequency.

If T_p is increased, system filters must be narrowed to maintain a comparable echo-to-reverberation ratio, but this procedure courts the difficulty inherent in construction of suitable narrow filters.

Possibly better suited to the exigencies of design is the second method in which there may be

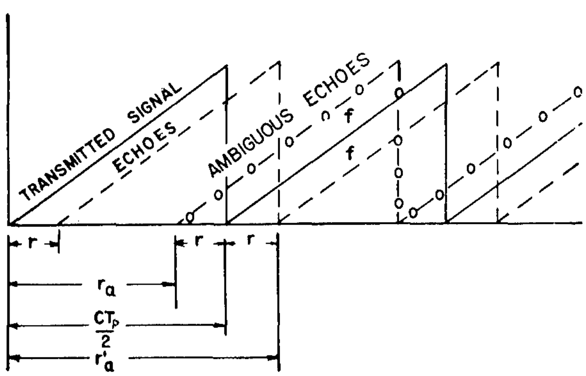


FIGURE 7. Strong targets at ranges r_a, r'_a may be interpreted as weak targets at range r, corresponding to frequency difference f.

selected such a frequency band that r_f of equation (7) lies near the maximum operational range, and the maximum difference frequency is limited to something of the order of one-fourth or one-sixth of the maximum sweep S.

The frequency band chosen should exhibit an attenuation coefficient [a in equation (7)] which results in a great difference between the range losses associated with its minimum and maximum frequencies. For example, if a mine has a target strength of about −12 db and a submarine a strength near 25 db, then it would be desirable to have at least 37-db difference between the range loss associated with the longest range for which true indication appears in the system and the shortest range capable of giving ambiguous (false) range indication in the system. Since r/r_a equals $\frac{1}{5}$, it is obvious that 40 log 5 is only 28 db. Hence attenuation must account for the remaining 9 db if a 37-db difference is to exist. If the maximum true range is 500 yd, then 17-db per kyd for a at 60 kc would provide the necessary loss, but 4 db for a at 24 kc would be insufficient. However, if 2,000 yd is the maximum true range the 16 db provided by an a of 4-db per kyd at 24 kc would be more than sufficient; hence, 24 kc is a sufficiently high frequency to prevent ambiguity of range indication in systems set for this longer maximum true range.

Reverberation measurements at UCDWR which have been analyzed[8, 9, 10] for frequency dependence, indicate that:

1. Volume reverberation increases with frequency at about 3 to 5 db per octave, which is much smaller than the 12 db per octave postulated by the Rayleigh theory of scattering.
2. Bottom reverberation shows no frequency dependence.
3. FM reverberations are characterized, in their coherent behavior, by the filter width of the analyzer; that is, blobs of reverberation have durations which are approximately equal to the reciprocal of the bandwidth, and are independent of range, position in sweep cycle, and sweep rate.

RECOGNITION DIFFERENTIALS

Recognition of a sonar contact is intimately related to the characteristics of a specific sonar system, the ability of its operator, and his familiarity with the system. This situation makes it difficult to generalize about recognition tests and almost useless to make specific references to them. Accordingly, in the following discussion an attempt is made to indicate which type of equipment may be expected to evince the best recognition differential characteristics for certain applications, and to indicate how recognition tests with FM systems may be made to yield significant results.

From the foregoing discussion of noise vs frequency and reverberation vs frequency in this section, it seems obvious that at long range, at least, the narrowest possible filter is desirable. Although this conclusion is based solely on the need for better signal-to-background ratio, the long-range portion of it is contrary to the usual desire of obtaining constant percentage accuracy in navigational work so that accurate

range information is obtained at short ranges. This latter effect is ignored for the present, but is discussed in Section 2.1.3.

What is the narrowest possible filter? In pulsed systems where the echo length is of a definite duration, i.e., when small target echoes show high coherence, a filter width (∂f) equal to the reciprocal of the pulse length would be the minimum width which would respond to full steady-state amplitude of the signal or echo. In FM systems the echo length τ may be of durations from continuous (if not scanning) down to that minimum time required for the hydrophone beam pattern to sweep past a given point, or to that time required for the interference patterns to change from one minimum to the next.

Let N rpm be the maximum anticipated rate of bearing scan. Then, if θ' is the effective hydrophone beam width in degrees, i.e., width between 6-db down points, the minimum echo length is approximately

$$\tau_N = \frac{60}{N}\frac{\theta'}{360} = \frac{\theta'}{6N}\text{ sec.} \tag{18}$$

However, if the frequency sweep rate is F_p/T_p then the time τ_m to sweep from one minimum to the next is

$$\tau_m = \frac{\Delta F}{F_p} T_p \tag{19}$$

where

$$\Delta F = (F_2 - F_1) = \frac{rc}{fh_1 h_2} \tag{20}$$

is the frequency difference from equation (5) required to produce a change of 2π in the phase delay patterns. Thus, equations (19), (20), and (13) give

$$\tau_m = \frac{T_p}{F}\frac{rc}{4h_1 h_2} = \frac{r}{f}\cdot\frac{r}{2h_1 h_2}. \tag{21}$$

For purpose of illustration substitute the following typical values in equations (18) and (21): $\theta' = 14$ degrees, $N = 5$, which gives $\tau_N = 0.47$ sec, or $\partial f = 2$ c. For $F_p = 12$ kc, $T_p = 2$ sec, $r = 100$ yd, $h_1 = h_2 = 20$ yd, and $c = 1{,}600$ yd per second, equation (21) now gives, $\tau_m = 1/60$ sec, or $\partial f = 60$ c. From these illustrative calculations it appears that filter widths of only a few cycles such as determined by rotation speeds alone are far too narrow to accommodate the fluctuations arising from interference effects.

Whether it is desirable for the system to portray these variations in intensity of the received signal must be determined by other considerations. For example, target size recognition by d-c response circuits with time constants corresponding to expected target echo lengths is one characteristic which may preclude rapid fluctuation reception. Also it should be pointed out that the signal length as determined by τ_N is the duration of the total group of maxima and minima with deviations of τ_m; and the narrow filter width determined by τ_N would give responses within about 3 db of the wider one determined by τ_m. Therefore a moderate compromise between the two filter widths is indicated.

In outlining a method of attack to determine recognition differentials applicable to FM echo-ranging systems it is important to distinguish between the terms *differential sensitivity* and *recognition differential,* and to define *dynamic range.*

Differential sensitivity is the 50 per cent detectable ratio of the sum $A + B$ of echo power and background power to the background power B, all within the linear portion of the receiver pass band. Note that these symbols are given in units of fundamental power measurement (dynes per square cm per second) as differentiated from the definitions of target strength T and background level β (in decibels) given in this section. Recognition differential is that 50 per cent detectable ratio of signal power A to background power B. Figure 8 gives the relation between the two.

Figure 9 is a typical plot of measurements in which either differential sensitivity or recognition differential is determined as a function of background level. It is apparent in Figure 9 that dynamic range of a receiving instrument is limited by the tolerable value of the system's differential sensitivity. In some studies the rec-

ognition differential chosen has been that corresponding to minimum differential sensitivity. In many cases the choice has established the value for dynamic range at zero. Since equipment, operating conditions, and general variations in background level are not always under complete control, one should select a working differential sensitivity or recognition differential which allows a reasonable dynamic range within which to operate.

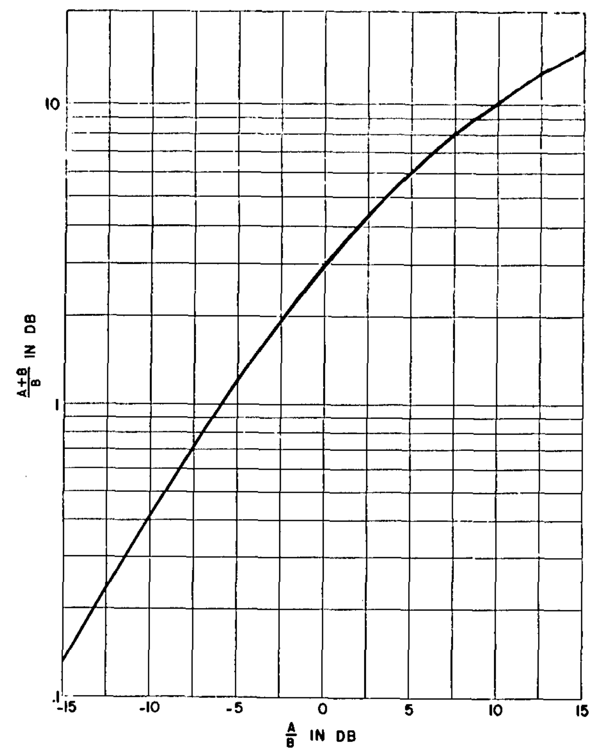


FIGURE 8. Both signal to background, ratio of powers A/B, and total power to background power ratio, $(A + B)/B$, are useful in describing differential recognition tests. Either may be determined from that one which is most readily measured.

Some informal tests on QLA recognition differentials, ∂, have been made at UCDWR, which indicate a value of $\partial = 0$ db for noise background. This result however is only preliminary and should not be taken as a final or ultimate value for prediction purposes. Further tests are necessary and should explore all anticipated combinations of parameter adjustments in receiving-indicating equipment.

2.1.3 Probable Errors in Observations

RANGE ERRORS

The basic assumption in FM echo ranging is that range may be determined by examination of the instantaneous difference between echo frequency and transmission frequency. Unfortunately, there are a number of factors other than range to target, which can affect the interpretation of this difference frequency, namely, (1) inhomogeneous medium, which causes varying velocities of propagation; (2) motion of projector and/or target with respect to medium, which causes doppler shifts in actual or effective frequency of echo; (3) variations in FM characteristics, e.g., the rate of change of frequency may not be constant; (4) uncertainties of frequency analysis, occurring in the receiver which is always limited by the frequency bandwidth of the analyzing filter; and (5) the error arising from portrayal of slant range as horizontal range.

An amplification of the assumption states that if the difference is known between echo frequency $F_c(t)$ and frequency of projection $F_s(t)$ at the time t, and, if the rate of change of projected frequency is known, then the elapsed time of two-way transmission is known; and therefore if the velocity of propagation is known, the range is calculable as half the two-way path. Mathematically the assumption may be described as follows. Let the projector frequency, as a function of time t be represented by $F_s(t)$, and its time derivative by $dF(t)/dt$. Then one may write

$$F_s(t) = F(0) + \int_0^t \left[\frac{dF(t)}{dt}\right] dt \tag{22}$$

where $F(0)$ is the projected frequency at time $t = 0$, e.g., at the time of the beginning of a sawtooth cycle. For the case of a linear sawtooth cycle $dF = F_p/T_p$ is constant such that

$$F_s(t) = F(0) + \frac{F_{p_t}}{T_p}. \tag{23}$$

If an echo is returned from a geometrical straight line range r, this range is approximated by

$$2r = \int_{t_0}^{t} c_i dt \tag{24}$$

which in turn is approximated by

$$2r = c(t - t_0) \tag{25}$$

where c is a previously determined average velocity of sound and c_i is the instantaneous velocity, and $t_0 = t - 2r/c$ is the time of emission of the wave now received as the echo. The echo frequency $F_e(t)$ is therefore given by

$$F_e(t) = F_s\left(t - \frac{2r}{c}\right)\left[1 + \psi(v)\right] = \left[1 + \psi(v)\right]\cdot \left[F(0) + \int_0^{t-\frac{2r}{c}} \left(\frac{dF}{dt}\right) dt\right] \tag{26}$$

where $\psi(v)$ is the doppler correction function of v, the approach component of relative velocity between projector and target. This function $\psi(v)$ is discussed later.

If f represents the difference $F_s - f_e$ then from equations (22) and (26)

$$\begin{aligned} f &= F_s(0) + \int_0^t \left(\frac{dF}{dt}\right) dt - \left\{F(0) + \int_0^{t-\frac{2r}{c}} \left(\frac{dF}{dt}\right) dt + \psi(v)\cdot \left[F(0) + \int_0^{t-\frac{2r}{c}} \left(\frac{dF}{dt}\right) dt\right]\right\} \\ &= \int_{t-\frac{2r}{c}}^{t} \left(\frac{dF}{dt}\right) dt - \psi(v)\, F\left(t - \frac{2r}{c}\right). \end{aligned} \tag{26a}$$

For the case where $\psi(v) = 0$ and $dF/dt = F_p/T_p$, equation (26a) becomes $f = F_p/T_p\ (2r/c)$ or $r = (T_p/2F_p)\ f$ as was given by equation (13).

The sources of error existing in FM systems as outlined in the first paragraph can be referred to in the equations assumed above. Thus, $c_i \neq c$, i.e., the average velocity is never known accurately, and therefore the range r is not strictly given by equation (25). This error, however, is inherent in all echo-ranging systems and is seldom[a] corrected for. In connection with such velocity uncertainties it may be remarked that since velocity dependence upon temperature is not a linear relation one might expect the measured velocity to depend not only on average temperature, but also upon the magnitude of the temperature fluctuations in the medium measured. Inhomogeneities also produce paths by refraction which are not equal to the geometric range r. Accordingly, equation (24) is not exactly accurate. For example, suppose a target at $h_2 = 98$ ft depth is detected by a projector $h_1 = 18$ ft depth, at geometric range of 1,000 yd by path of circular (radius R) grazing incidence[11] at the surface. (See Figure 10.) The path length exceeds the straight line path by about 1 yd. Further, if both target and projector are 100 ft below the surface, and the geometrical range at grazing incidence is 1,000 yd, the excess of path over straight line distance is still only about 3 yd. Since the change of sound velocity in sea water with temperature is roughly 0.1 per cent per degree F, situations exist where the actual velocity may differ from assumed velocity by as much as 0.5 per cent, which means a range error of 5 yd in 1,000. Accordingly, it seems that incorrect values of mean velocity can produce more range error than does the thermal gradient but that neither is greatly significant.

[a] The Navy has had systems under development to account for average temperature effects, but not for magnitude of fluctuations at a point or along the path.

Equation (26) states that the echo frequency is dependent upon the motion of either the target, projector, or hydrophone with respect to the medium. First, let the projector emit sound at frequency F_0 and have a velocity v_p toward the target, then the sound frequency in the water would be

$$F = F_0 \frac{1}{1 - v_{p/c}}. \tag{27}$$

If instead, the target has a velocity component v_t toward the projecting vessel, the increase in frequency is

$$\frac{v_t}{\lambda} = v_t \frac{F_0}{c},$$

where λ is the wavelength, and the new received frequency at target is

$$F = F_0\left(1 + \frac{v_t}{c}\right), \tag{28}$$

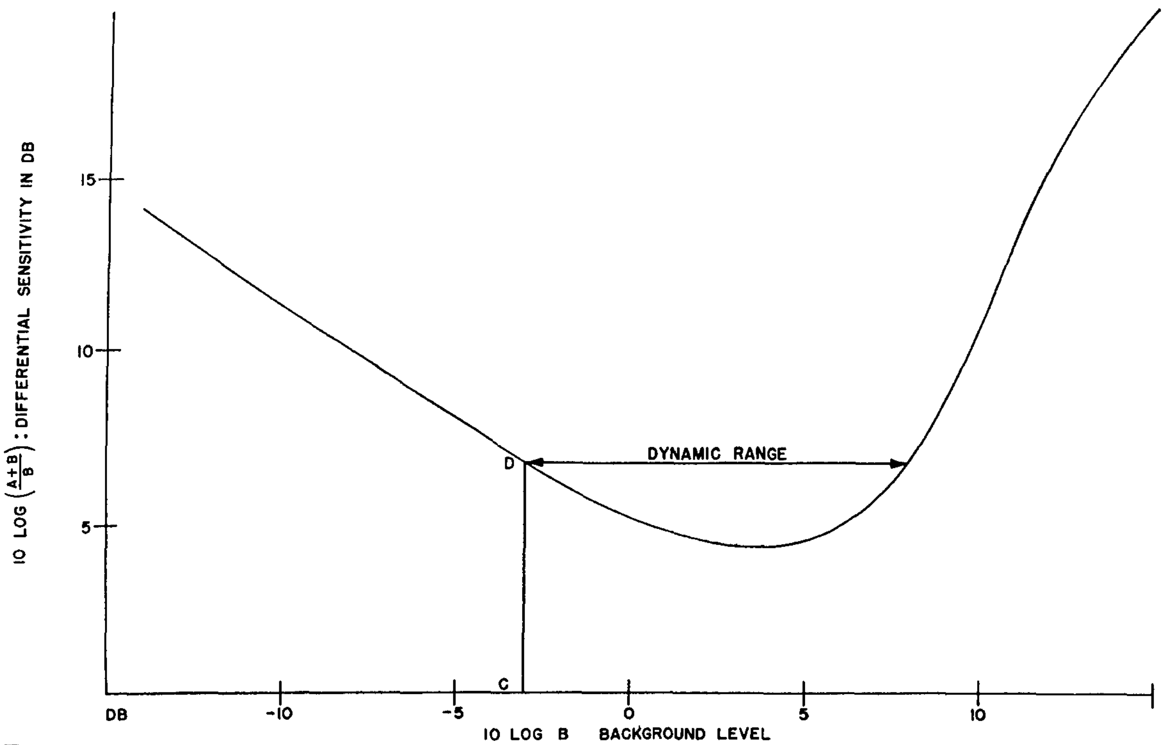


FIGURE 9. The dynamic range of a receiver indicator is a function of the maximum tolerable differential sensitivity, *CD*.

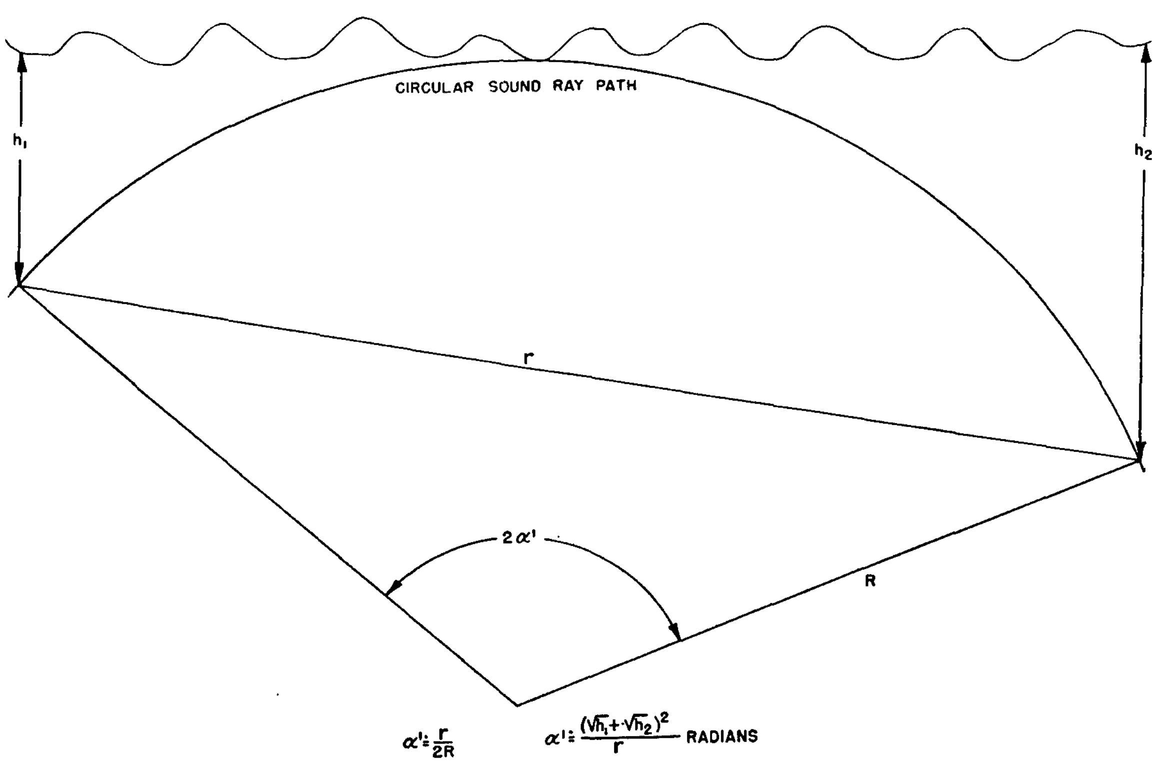


FIGURE 10. Only slight deviations from geometrical path length, *r*, result from sound rays following circular paths in medium of constant velocity gradients.

and therefore the frequency reflected, using equation (27), is

$$F = \frac{F_0\left(1 + \frac{v_t}{c}\right)}{1 - \frac{v_t}{c}}. \qquad (29)$$

Now at the moving projector or hydrophone the frequency is again changed by the interception of more wave maxima per second, and one obtains, using equations (27), (28), and (29):

$$F = F_0 \frac{\left(1 + \frac{v_t}{c}\right)\left(1 + \frac{v_p}{c}\right)}{\left(1 - \frac{v_t}{c}\right)\left(1 - \frac{v_p}{c}\right)}$$

$$= F_0 \frac{\left(1 + \frac{v}{c}\right)}{\left(1 - \frac{v}{c}\right)}$$

$$= F_0\left(1 + 2\frac{v}{c}\right) \qquad (30)$$

where $v = v_p + v_t$ now represents the total velocity component of approach between the target and echo-ranging ship and F_0 is the actual frequency of projector oscillation now received as frequency F after having been reflected from the target.

Thus the doppler function $\psi(v)$ is given approximately by $2v/c$, and the frequency difference f from equation (27) becomes

$$f = \int_{t-\frac{2r}{c}}^{t}\left[\frac{dF}{dt}\right] dt - 2\frac{v}{c}\left\{F(t) - \frac{2r}{c}\right\}. \qquad (31)$$

For the case of the constant $dF/dt = F_p/T_p$ one has

$$f = \frac{F_p}{T_p}\frac{2r}{c} 2\frac{v}{c}\left\{F_p(0) + \frac{F_p}{T_p}\left[t - \frac{2r}{c}\right]\right\} \qquad (32)$$

which when solved for r becomes approximately,

$$r = \frac{T_p c}{2F_p}\left\{f + \left[F_p(t) - f\right]\frac{2v}{c}\right\}. \qquad (33)$$

Thus it becomes apparent that even for the case of the ideal linear sweep, the actual range is not proportional to the frequency difference f and that the deviation from proportionality is not constant, but depends upon the portion of the sweep cycle as well as upon the difference f.

An example illustrates the magnitude and relative importance of the range errors caused by doppler shifts indicated by equation (33): Let $T_p c/2F_p = 1$ yd/c, and $2v/c = 0.007$, i.e., $v = 10$ knots then the 2,000-c filter passes echoes from targets at ranges 2,238 yd and 2,322 yd when the projector frequency is 36 and 48 kc, respectively, while for $v = 0$ the range would be constant at 2,000 yd. Thus a shift of 280 yd average is found with 84 yd variation throughout the sweep. For the 500-c filter the ranges are 748 and 832 yd or an average shift of 290 yd with an 84-yd variation. It is thus apparent that even for very slow speeds, say $v = 1$ knot, the doppler range errors are far larger than any other effect discussed in this report.

Some FM systems sweep up, and some sweep down. Equation (33) suffices for either if proper signs are used for T_p/F_p and for $f = F_s - F_e$. Since modulators are not sensitive to whether f is positive or negative there may be short-range doppler ambiguities unless responses are limited to frequencies above a certain value.

If the frequency sweep is up then echo frequencies are lower than projected frequencies, and the error produced by an up doppler (approaching) would be toward shorter range indication, while if the sweep is down the reverse is applicable and approaching target would produce longer than actual range indication by the same amount. Receding doppler produces opposite effects. The four possibilities are summarized in the following table to indicate range error: + means indicated range is too large, and − means indicated range is too small.

Doppler \ Sweep	Up	Down
Up	−	+
Down	+	−

While effect of doppler gives rise to errors in range indication in QLA-1 (and similar sys-

tems), it was turned to advantage in an FM system known as Subsight, which utilized the doppler effect to compensate exactly for range error and furnished time-to-fire for ahead thrown weapons.[12, 13] Current with the date of this report, consideration is being given to modification of QLA-1 for the presentation of instantaneous range-rate information by the doppler effect.

In order that the frequency difference of echo and projection shall have accurate numerical significance in presenting range or time-delay information, it is necessary to know precisely the frequency modulation characteristics of the sonar transmitter. Equation (31) would permit other functions than a constant to be inserted for dF/dt, but ambiguities of range would immediately result. Such ambiguities would become important if the deviations from nonlinearity were large compared to the individual filter bandwidths employed to analyze the frequency difference f but present design seems to have achieved linearity of frequency sweep adequate to the 75-c filter widths employed. In fact, the filter widths employed may be used as criteria for assignment of relative importance to all known range errors in the FM system. Thus in terms of 75-c filters, the doppler errors are the only ones so far determined which need greatly concern the designer. However, if the theoretical minimum filter widths of 2 c or even 8 c were employed to give better range accuracy, the range errors (mentioned in preceding text) other than that induced by doppler would assume greater significance.

Bearing Errors

Since bearing is the other one of the principal observables in echo ranging, it is the purpose of these paragraphs to outline a discussion of factors affecting bearing accuracy in FM systems. The method of obtaining bearing by a rather sharp directional lobe associated with the receiving hydrophone has already been introduced. Bearing accuracy may be increased by narrowing the lobe width, but in ordinary echo-ranging systems the probability of maintaining contact with the target is much reduced when lobe widths become as small as 4 to 5 degrees, because of pitch and roll of the ship during intervals between pings, and of pinging at times of poor transmission. An FM scanning system, however, is ideally continuous in its transmission and reception, so that there is no dead time other than that caused by interference fluctuations. In practice, because of the cyclical character of the continuous transmission, there is also associated with each modulation period a lost-time interval in which the frequency-time pattern reestablishes itself. (See Section 8.1.3.) A typical period of interference fluctuations [for $r = 100$ yd, $h_1h_2 = 160$, $T_p = 3$ sec, and $F_p = 12$ kc from equation (21)] is of the order of 0.06 sec, while the training rate of 30 degrees per second gives signal lengths of about 0.5 sec for 14-degree beam widths. For short ranges, it would thus seem possible to reduce hydrophone beam width to about 4 degrees and still be assured of being trained on the target for 0.12 sec during which at least two maxima of the interference pattern would produce detectable signals. Such a beam would have better reverberation or directivity index, thus improving the echo-to-reverberation ratio by at least 6 db, and would reduce the uncertainty of bearing by a factor of four. Of course, this would bring minimum filter widths up to 8 c, but this is far below the usual 75-c bandwidth. Such narrow filters would probably never be required because of limitations on equipment bulk. Therefore narrower beams seem in order and would be immediately practicable at high frequencies for short-range problems. Long-range problems must use either wide beams or slow training rates to include one maximum due to the image effect. (See Section 2.1.2.)

The success of bearing deviation attachments and designs on standard pinging systems suggests that BDI should be tried on FM sonar. Fundamentally there seems to be no reason to avoid its use other than the difficulty of achieving satisfactory nonambiguous presentation of the information to the operator. However, since BDI was introduced on pinging systems to aid in reducing the time required to obtain a bearing on a target, the same argument does not hold in FM scanning echo-ranging systems since the time to obtain a bearing is only deter-

mined by sweep rates, and its accuracy by beam width. Therefore, if the beam were narrowed in the manner described, similar amounts of improvement could be expected for FM systems as was given pinging systems by BDI.

Current with the date of this report, FM systems intended for scanning operations employ a projector beam approximately 90 degrees wide and a hydrophone beam about 14 degrees wide. The two-way beam pattern, therefore, is that of the hydrophone alone. It appears possible and perhaps practicable to employ narrower hydrophone beams in FM systems for sharper definition of bearing indication.

2.2 BASIC DESIGN CONSIDERATIONS

The design considerations discussed in the following text have been evolved by application of the foregoing principles to the construction and operation of developmental systems culminating in QLA-1.

2.2.1 Intrasystem Relationships

Certain general considerations should be taken into account in developing the overall plan of any frequency-modulated echo-ranging system. These general considerations are discussed before attention is turned to the basic design considerations pertinent to specific system components.

Average Frequency

Of prime importance in the design of any FM system is the choice of transmission band because it determines so many of the parameters of the system. Transmission band is discussed here in terms of its average frequency. In selecting the average frequency a compromise must be effected between requirements for extreme range and requirements for extreme definition of targets. The final choice depends upon the purpose for which the system is intended.

Another aspect of this problem involves the relation between extreme directivity (at a given frequency) and size of the crystal (or magnetostriction) array in the transducer. For a given directivity, lowering the frequency requires that the dimensions of the array be increased. Transducer size may thus become a limiting factor on range capabilities of the system in that the array required to maintain desired directivity (at low frequencies favorable to long range) may be so bulky as to be impractical.

On the other hand, as the frequency increases it is necessary to reduce the dimensions of the array in order to maintain a desired beam pattern. The limiting factor in this progression is the point at which the array (because of its reduced size) is no longer capable of putting sufficient power into the water.

Width of Swept Band

The ideal transmission band would be infinitely wide in order to eliminate range ambiguity at any maximum true range. As of the present stage of the FM system development the limitation on width of transmission band is the frequency response of transducers. In the present state of the art (QLA-1) this consideration fixes minimum and maximum frequencies approximately in the ratio of 3/4. It is obvious that this 3/4 ratio, when considered in conjunction with the average frequency or center point of the band, limits the width of the transmission band in a rather definite manner.

Swept Band vs Receiver Pass Band

The width of the swept band should be as great as possible with relation to the width of the receiver to minimize range ambiguities which arise in all FM systems because the cyclical character of the transmitted signal makes it possible for targets at increasing ranges to return echoes which give the same difference frequency when heterodyned with the transmitted signal. With the maximum width of the swept band determined by the 3/4 ratio mentioned in the preceding paragraph, the relationship between width of the swept band and width of the receiver pass band is then achieved by varying the width of the latter.

Figure 11 illustrates the situation obtaining with a 5-kc pass band and a 12-kc swept band.

Here the maximum true range is 1,000 yd, and the first ambiguous range (image) is 1,400 yd. Echoes returned from both these ranges produce the same difference frequency (5 kc) when heterodyned with the transmitted signal. Because of the small separation in range of these two targets, their echo amplitudes would not be differentiable.

Reducing the width of the receiver pass band to 2 kc as illustrated in Figure 12, the maximum true range becomes 400 yd, and the first ambiguous range becomes 2,000 yd. The 1,600-yd separation between these two targets is now great enough (a 1/5 ratio) so that the two signal strengths are easily differentiable.

To minimize range ambiguity by restricting the receiver pass band, and *without restricting range,* the sawtooth period may be lengthened as illustrated in Figure 13. Here, the sawtooth period has been increased from 3 sec (as illustrated in Figures 11 and 12) to 12 sec with the result that the 400-yd echo returns when the elapsed fraction of the sawtooth period is relatively smaller than it was under the conditions obtaining in Figure 12. Hence the difference frequency has been reduced and greater ranges may be accommodated by the 2-kc receiver pass band. With the sawtooth period increased to 12 sec the longest true range of which the system is cognizant has become 1,600 yd and the nearest ambiguous range has become 8,000 yd. Ranges of the latter order rarely produce indications in present sonar systems.

It will be noted that the relationship between the maximum true range and the minimum ambiguous range under those conditions illustrated in Figures 12 and 13 is in the ratio of 1/5, while for the conditions depicted in Figure 11 the ratio was 1/1.4. The values of these ratios derive from the relationship between the width of the receiver pass band and the width of the swept band, and may be expressed as follows:

$$\frac{\text{(Max true range)}}{\text{(Min ambiguous range)}} = \frac{\text{(Receiver pass band)}}{\text{(Swept band)} - \text{(Receiver pass band)}}$$

By application of this formula in the selection of widths of swept band and receiver pass band, occurrence of ambiguous range indications becomes a design parameter.

Power in Water

The amount of power put in the water by an FM system depends in general on the purpose for which the system is intended, but more particularly on the relationship of a number of specific considerations.

For an ideal system,

$$W = P^2 r^2 A = \frac{4\pi 10^{-7}}{\rho c}$$

in which

W is a power required (from the driver amplifier) in watts;

P is rms sound pressure required in dynes per sq cm;

r is a distance in cm at which the sound pressure is specified;

A is the fraction of the total sphere that is to be illuminated (intercepted by the solid angle of transmission);

ρc is $1.5 \times 10^5 \times$ (gm/sec$\times$sq cm) for sea water.

For a real projector the power has to be increased by a factor $1/E$ where E is the actual efficiency of the projector.[b]

The factor A is replaced by a factor D which is the actual directivity factor of the projector and is generally somewhat larger than A if the required pressure is to be maintained over the specified solid angle of transmission. In addition it is necessary to compare the directivity patterns of the projector to the solid angle of transmission in all pertinent planes to determine the actual pressure as compared to the desired pressure at all points on the surface of that fraction of the total sphere intercepted by the solid angle of transmission.[c]

Range Resolution vs Range Comprehension

Multifilter analysis of the output of the first detector sets range resolution in opposition to range comprehension, because of the physical bulk of the large number of filters required to achieve the former in the presence of the latter.

[b] See Division 6, Volume 7, Section 1.1, "Large and Small Sources in an Ideal Medium-Directivity."

[c] See Division 6, Volume 12, Section 4.3 and 4.4, "Directivities."

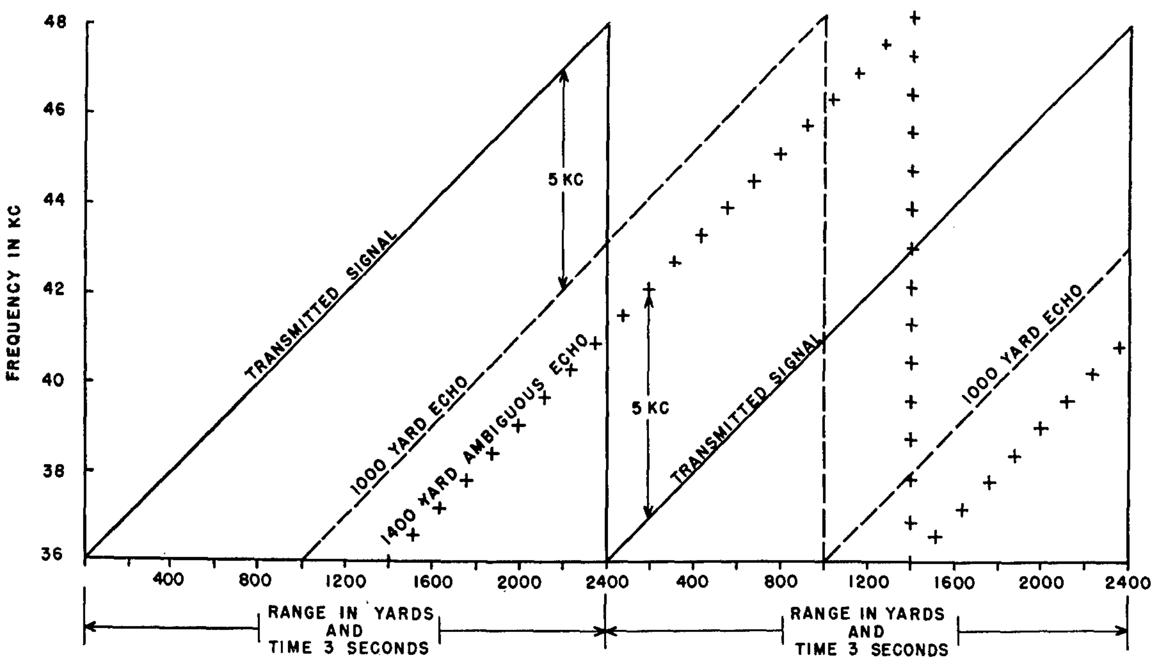


FIGURE 11. Echoes from targets at different ranges giving same difference frequency: true and ambiguous range indications.

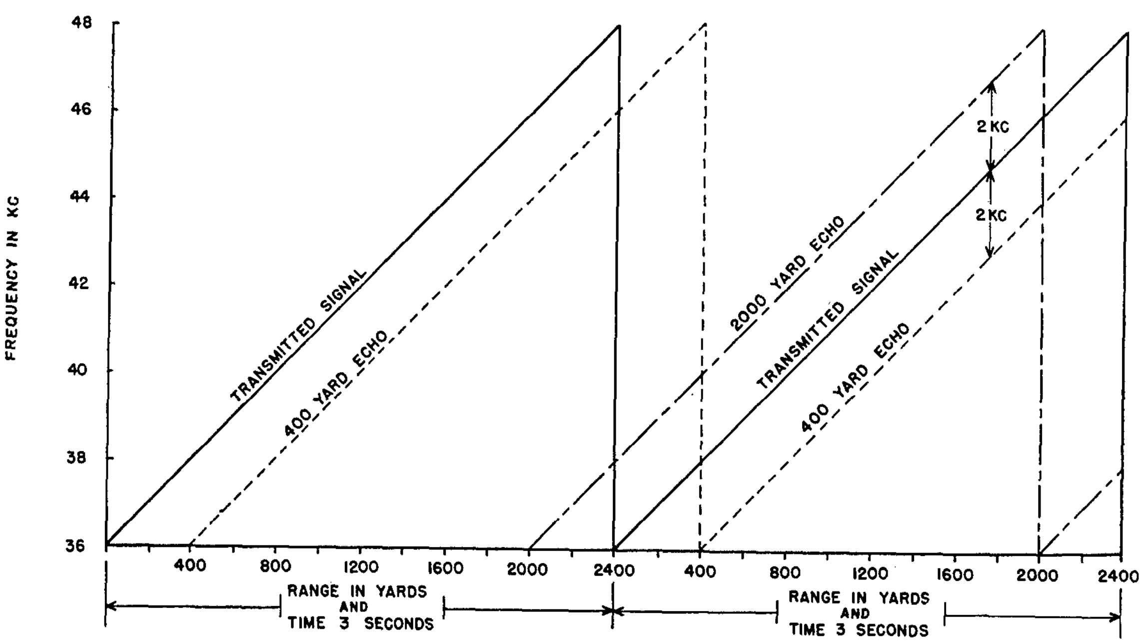


FIGURE 12. Restriction of receiver band pass minimizes ambiguous range indication.

For example, assume a system capable of simultaneous comprehension of ranges from zero to 2,000 yd and employing a 2,000-c receiver pass band. Then for ideal range resolution (say lineal in 5-yd increments) such a system would require 400 filters, each having a bandwidth of 5 c. For most applications such a large number of filters is obviously impractical. If it is supposed that practical considerations the system is simultaneously cognizant are in the ratio of 1/4. Thus, on the 3,000-yd maximum range scale, the 2,250-yd difference between minimum and maximum ranges is divided into 20 increments of 112.5 yd. Shorter ranges (under 750 yd) are scanned by shortening the length of the sawtooth modulation cycle, so that the system may be made to scan 300 to 1,200 yd, 150 to 600 yd, 75 to 300 yd, and

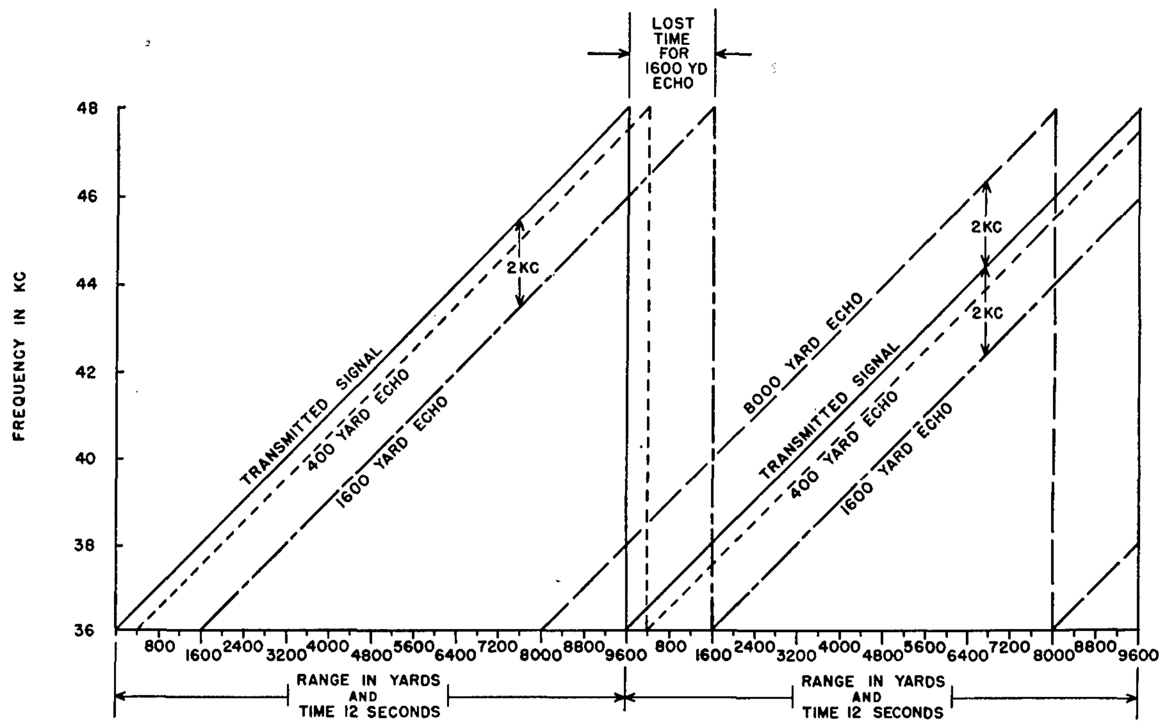


FIGURE 13. Lengthening of sawtooth period minimizes ambiguous range indication.

limit the number of filters in the system to 40, then two alternatives are open.

1. Maintain range comprehension by expanding filter bandwidths to 50 c at the sacrifice of range resolution which would now exhibit 50-yd increments.

2. Maintain range resolution by reducing the comprehension of the system to a bandwidth of only 200 c (40×5). Under these conditions range comprehension is only 1,800 to 2,000 yd, for example.

This conflict is resolved in QLA-1 analysis of a 2-kc spectrum by 20 filters so arranged that the minimum and maximum ranges of which 25 to 100 yd in range increments of 45, 22.5, 11.25, and 3.75 yd, respectively.

Distribution of filters throughout the spectrum may be made in any manner which serves the purpose for which the system is intended, but three more or less standard arrangements are: (1) direct logarithmic progression in which the filter widths increase with increasing frequency to give a constant *percentage* range accuracy; (2) inverse logarithmic progression in which the filter widths *decrease* with increasing frequency to afford approximately uniform discrimination against reverberation throughout the spectrum; and (3) linear distribution of

equal-width filters throughout the spectrum to give constant unit range accuracy.

RATE OF BEARING SCAN

PPI presentation is achieved by a continuous azimuth scan with which the indicator trace is synchronized. Three ways in which this may be accomplished are: (1) by the use of a fixed 360-degree projector and a fixed 360-degree hydrophone, the latter being composed of a number of circumferential segments so connected that its major sensitivity may be rapidly scanned in azimuth by phase-shifting networks; (2) by the use of a fixed 360-degree projector with which is associated a mechanically rotated directional hydrophone; or (3) by the use of a projector whose beam width is something less than 360 degrees, a directional hydrophone so positioned that the axis of its major lobe corresponds to the axis of the projector's major lobe, and the two transducers mechanically rotated as a unit.

FM systems have so far mainly utilized only the last of the three possibilities mentioned above, in which the maximum rate of azimuth scan is determined by the following considerations: (1) the beam width of the receiving hydrophone vs the bandwidth of the analyzer channels, and (2) the range vs the beam width of the projector (see Figure 11, Chapter 5). At extreme rates of transducer rotation the noise level associated with turbulence at the transducer face could also become a limiting factor on rate of bearing scan.

In explanation of (1) the maximum scanning rate is limited by the response time of the individual filter ($1/fw$) and the angular width of the hydrophone beam (θ_h). The maximum allowable scanning rate is such that the time during which the target is within the hydrophone beam equals the filter response time, and may be derived in terms of rpm as follows.

$$\text{Since} \qquad \frac{1}{fw} = \frac{60 \times \theta_h}{\text{rpm} \times 360},$$

$$\text{rpm} = \frac{fw \times \theta_h}{6}$$

in which θ_h is in degrees, and fw is in cycles per second. This allows approximately 150 RPM with QLA-1.

For (2) the maximum scanning rate is limited by the beam width (θ_p) of the projector vs range (r). The maximum allowable scanning rate is such that the soundhead rotates less than $\theta_p/2$ during the time required for sound to travel to the target at range r and back to the hydrophone (assuming as set forth that the hydrophone is centered in a projector beam less than 360 degrees in width). Maximum allowable scanning rate may be derived in terms of rpm as follows.

$$\text{Since} \qquad r = \frac{\frac{\theta_p}{2} \times \frac{1600}{2}}{360 \times \frac{\text{rpm}}{60}} = \frac{200 \times \theta_p}{3\ \text{rpm}},$$

$$\text{rpm} = \frac{200 \times \theta_p}{3r}$$

in which θ_p is in degrees, and r is in yards. The 1600/2 in the first expression represents the round trip time of sound to the target at velocity of sound in water of 1,600 yd per sec. (See Figure 11, Chapter 5.)

2.2.2 Frequency-Modulated Oscillator

The performance requirements that must be met by the frequency-modulated oscillator are very strict, and considerable care must be exercised in its design to insure proper operation.

There are several ways to obtain the necessary frequency-modulated signal for an FM system as indicated in Section 3.1.4. For a number of reasons, also indicated in Section 3.1.4, the method used in QLA-1 seems to be the most satisfactory in the present state of the art. Accordingly, the following discussion outlines the basic design considerations pertinent to this method.

The complete frequency-modulated oscillator used in QLA-1 consists of four essentials: (1) a voltage sensitive oscillator, (2) a sawtooth voltage generator, (3) an exceptionally well-regulated power supply, and (4) a blanker-synchronizing circuit.

VOLTAGE SENSITIVE OSCILLATOR [VSO]

The VSO is a unique type of multivibrator operating with a positive bias. The characteris-

tics of the positive bias multivibrator are such that the frequency of its output can be controlled over a wide range by varying the bias voltage applied to its grids. With proper choice of circuit parameters it is possible to obtain the highly linear voltage-frequency relationship so essential to FM operation.

In general, the period of a positive bias multivibrator is dependent on (1) the amplitude of

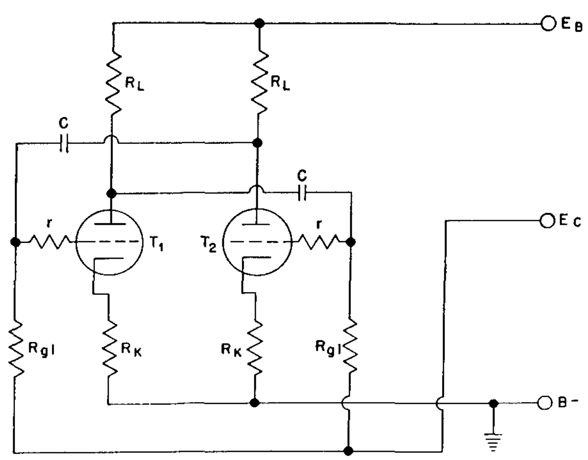


FIGURE 14. Positive bias multivibrator, simplified schematic diagram.

the oscillations, (2) the RC combination in the grid circuit, and (3) the voltage to which the grids are returned. A complete treatment of the subject is beyond the scope of this report, but certain experimentally developed curves are useful in selecting the circuit parameters important to the establishment of a linear voltage-frequency relationship throughout various transmission frequency bands. The curves presented below have been derived experimentally, because mathematical analysis of the functions portrayed has not so far proved applicable to the practical problems of design. Because of the experimental nature of the derivation the curves shown in Figure 15 cannot be assumed to be correct for a circuit employing other than the 6J5 tubes identified in Figure 14.

Figure 14 is a simple schematic diagram of the circuit used to obtain the curves. The tubes are two 6J5 triodes, and the associated resistors, condensers, and voltages are identified and referred to in the curves. The two resistors r connected in series with the tube grids suppress parasitic oscillations that may otherwise occur when the grids are positive.

Figure 15 illustrates the relation existing between frequency output and positive-bias vs plate-supply voltage for different values of cathode resistors but with other circuit parameters remaining constant. The areas in which the curves themselves are linear is indicative of the degree to which the variables may be changed without adversely affecting the linearity of the basic voltage-frequency relationship. The angular slope of the curves is indicative of the amount of frequency change (in cycles per

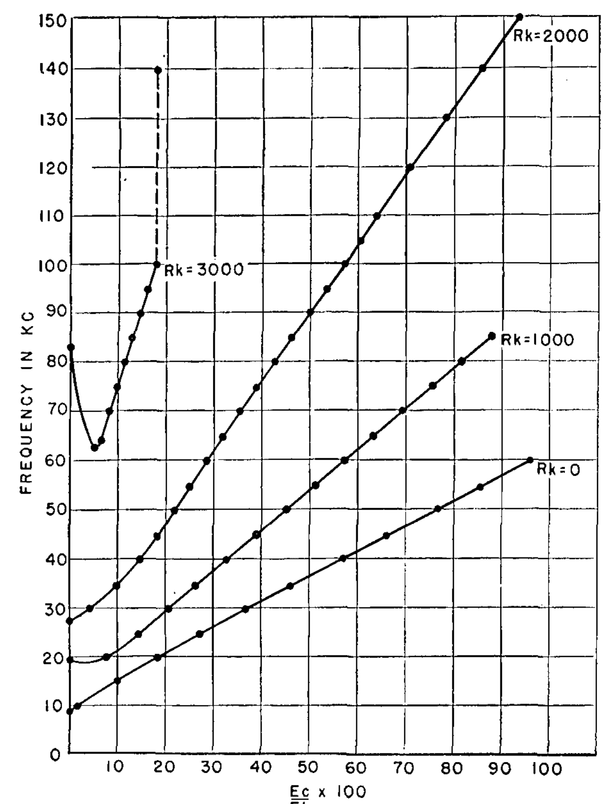


FIGURE 15. Positive bias multivibrator, frequency vs voltage.

second) for a given increment of change in positive bias. This relationship may be spoken of as sensitivity of frequency change to change in positive bias. In general, sensitivity increases with an increase in the value of cathode resistor (*Rk* in Figure 14). It will be noted (Figure 15) that the curve for *Rk*—1,000 ohms and the curve for *Rk*—2,000 ohms are both linear be-

tween the two values of 20 and 90 for 100 *(Ec/Eb)*. The curve for $Rk = 0$ exhibits curvature between the two above values, greater than the permissible 0.1 per cent, and hence zero value for *Rk* is not recommended for present FM system design practice. (The curvature of $Rk = 0$ is not very apparent in Figure 15, because 0.1 per cent variation from true linearity is difficult to portray in this size illustration.) It is obvious that for values $Rk = 3{,}000$ ohms and more, that the multivibrator is unstable.

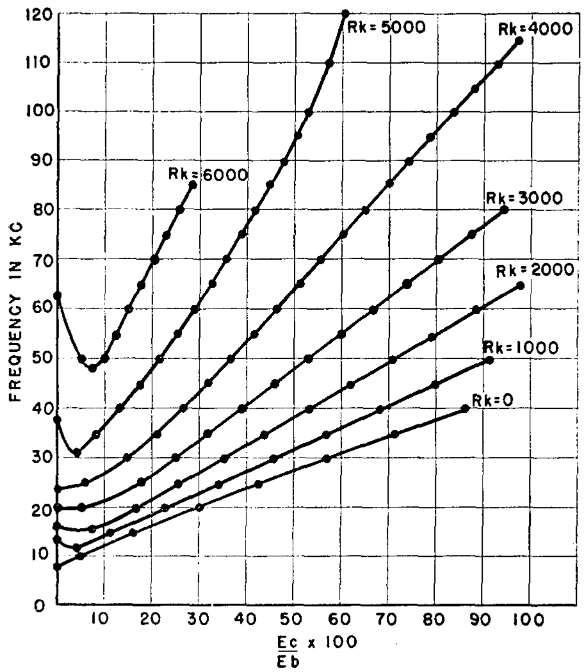


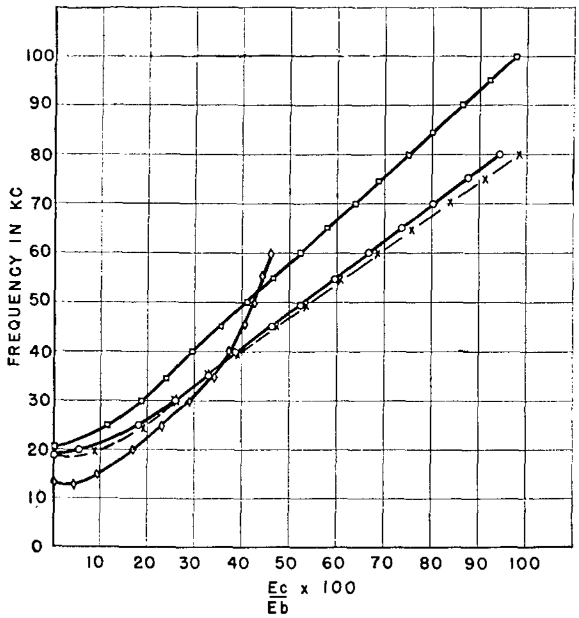
FIGURE 16. Positive bias multivibrator, effect of plate load resistance on sensitivity.

For conservative design, values of *Rk* should be held between 1,000 and 2,000 ohms.

Figure 16 is a group of curves similar to those in Figure 15, but here the value of the plate load resistor (*Rl* in Figure 14) is double that used in preparation of the Figure 15 curves. Sensitivity still increases with an increase in the value of *Rk*, but a general reduction in sensitivity results from the increase in the value of *Rl*.

Figure 17 illustrates the effect of varying the ratio grid-resistor (*Rgl*, Figure 14) vs coupling condenser (*C*, Figure 14) throughout the particular range frequencies appearing in Figure 17. These experimental curves indicate the desirability of maintaining *Rgl* at a value in keeping with normal resistance-coupled amplifier design, i.e., in the region between 100,000 and 500,000 ohms.

Figure 18 illustrates variation in frequency of multivibrator output as determined by changes in the ratio *Ec/Eb*, with the plate supply *Eb* held constant. It is obvious that all curves from 25 to 75 kc inclusive are uniformly displaced from each other throughout their entire length. This uniform displacement is indicative of linearity in the relationship between *Ec/Eb* and the output frequency, and hence defines the limits within which the variables may be changed without adversely affecting the output linearity. The foregoing experimentally derived curves have proved useful as a guide to the selection of circuit parameters which would assure operation of the positive bias multivibrator within its most linear range.



$R_L = 10{,}000,\ R_K = 3{,}000$

R_{gl}	C
◇—27K	1000 $\mu\mu$fd
×—135K	200 $\mu\mu$fd
○—270K	100 $\mu\mu$fd
□—540K	50 $\mu\mu$fd

FIGURE 17. Positive bias multivibrator, region of acceptable linearity.

A more detailed treatment of the characteristics of the positive bias multivibrator follows.

The multivibrator is well known and much has been written about its operation.[14] The use of a multivibrator

operating with positive bias[15] is comparatively new, however, and its extremely useful characteristics are not well known. The positive bias multivibrator is a simple oscillator whose frequency can be controlled over a wide range by varying the bias voltage. The extremely linear relationship obtainable between voltage and frequency makes it adaptable to a wide variety of uses.

The positive bias multivibrator (Figure 14) consists of a two-stage resistance coupled amplifier with the output coupled directly back to the input so that the circuit is regenerative. The mode of operation (of the multivibrator) is quite easily seen. Let a switch (not shown in figure) connected in series with the cathode of T_2 be closed at Time A (Figure 19). Since the grid erating the already rising voltage on the grid of T_1. When T_1 becomes sufficiently conducting to make the combined gain of T_1 T_2 greater than unity the circuit flips-over, i.e., functionally the two tubes change places, the grid of T_1 becoming positive with respect to its cathode and T_2 being driven beyond cutoff. The operation is then repeated except for the tubes having changed places, the grid of T_2 rising exponentially until T_2 becomes conducting and a second flip-over occurs.

If the multivibrator is perfectly balanced, it is possible that when operating voltages are applied, oscillations will not immediately start. In this case, both tubes are highly conducting with their grids positive. Two conditions are now possible.

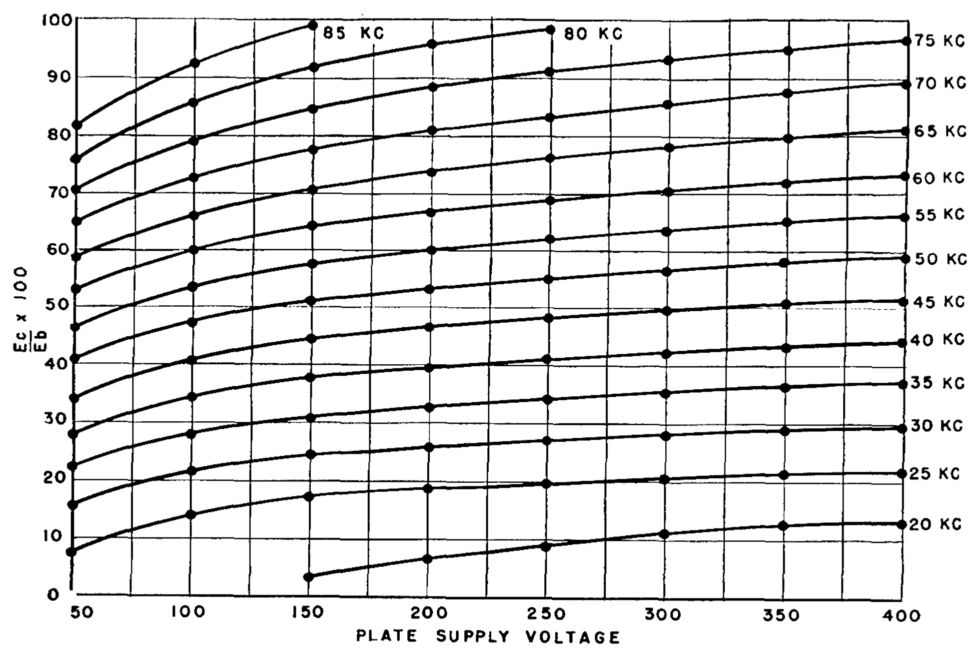


FIGURE 18. Positive bias multivibrator, uniform displacement of frequency curves.

return of E_C of T_2 is positive with respect to the cathode return ($B-$), T_2 immediately becomes highly conducting resulting in a drop in voltage at the plate of T_2. This drop in voltage coupled through condenser C to the grid of T_1 is sufficient to drive the grid of T_1 beyond cutoff. Thus, at the beginning of the cycle, T_1 is cut off and its plate is at substantially the voltage of the supply. T_2 has its grid positive with respect to its cathode and considerable drop across its plate load. The voltage to the grid of T_1 now rises as the coupling condenser charges. The voltage now approaches the voltage of the grid supply. E_C for a time as shown by the dotted line. When the grid of T_1 becomes sufficiently positive, T_1 starts to conduct (B in Figure 19) so that its plate and the grid of T_2 with the plate of T_1, become increasingly negative. The reduction of voltage on the grid of T_2 causes its plate and the grid of T_1 with the plate of T_2, to become increasingly positive thus accel-

1. The total gain of the circuit with the grids positive is greater than unity; then any small fluctuation in the circuit is amplified until it is sufficient to start the multivibrator cycle.

2. The total gain is less than unity; in this case fluctuations in the circuit are suppressed and the multivibrator is not self-starting.

The period of the multivibrator is dependent on the amplitude of the oscillations, on the resistance-capacity combination in the grid circuit, and on the voltage to which the grids are returned. The half-period is very nearly the time necessary for the grid voltage to change from its highly negative value following flip-over to the cutoff value. The period is increased by: (1) increasing the amplitude of oscillations by increasing the plate load resistance; (2) increasing either the resistance or capacity in the grid circuit thus decreasing the rate at which the condenser charges; (3) increasing the grid

return voltage E_C thus increasing the rate at which the condenser charges.

The preceding qualitative analysis has neglected several factors whose effect on the multivibrator operation is normally quite small though observable. These secondary factors include:

1. The time constant in the plate circuit affects operation. At the flip-over the grid going positive is carried more positive to (e_{g4}) than the static equilibrium voltage (e_{g3}) and decreases at a rate determined

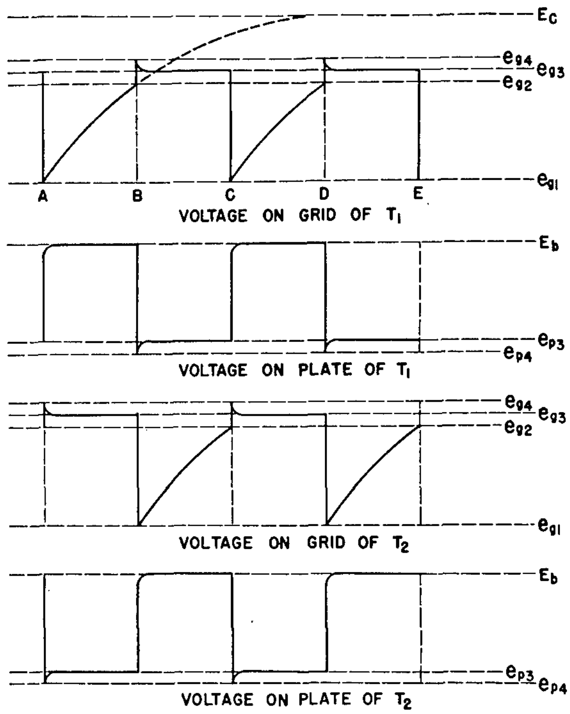


FIGURE 19. Positive bias multivibrator, time relationships.

by the plate circuit time constant to the equilibrium value.

2. The grid voltage variation of (1) is accompanied by a corresponding plate voltage change e_{p4}—e_{p3}; thus the character of the grid voltage change in the cutoff tube is modified somewhat from the simple exponential form.

3. Instantaneous changes in the voltages at flip-over are prevented by the tube capacities; thus, when at A in Figure 19 T_1 is cut off, its plate voltage does not immediately become equal to the supply voltage but rises rapidly to it.

4. The voltage change in the plate circuit is not carried over in its entirety to the grid circuit, the voltage dividing between the tube input capacity and the coupling condenser; this effect becomes appreciable only when the coupling condensers are small.

Mathematical analysis: An exact analysis of the action of the positive bias multivibrator would have to consider the operation of the vacuum tubes at both extremes of operation (near cutoff and with positive grid). Such an analysis would have to rely on experimental data on the tubes used which is generally not available. The following calculation of the frequency of a positive bias multivibrator is based on several simplifying assumptions.

1. The plate current of the tubes is expressed by the formula

$$i_p = \frac{E_b + ue_g}{R_p + R_L}.$$

2. The grid resistance of the tubes is zero so that the grids are never positive with respect to their cathodes.

3. Tube capacities are negligible.

4. The time constant in the plate circuit is sufficiently small in comparison to that in the grid circuit to enable the plate circuit to reach equilibrium before the opposite tube starts to conduct.

The significant voltages (Figures 14 and 19) can now be calculated for each tube. Those required to calculate the frequency of operation are the equilibrium voltage in the grid circuit e_{g3}, the cutoff voltage e_{g2}, the maximum negative voltage e_{g1} and the plate voltage when the tube is conducting e_{p3}.

A. *Calculation of e_{g3} and e_{p4}.*

$$i_{p3} = \frac{[(E_b - i_pR_L - i_pR_k) + u\,(e_g - i_pR_k)]}{R_p},$$

$$= \frac{(E_b + ue_g)}{R_p\left[1 + \dfrac{R_L}{R_p} + \dfrac{R_k}{R_p} + \dfrac{uR_k}{R_p}\right]}.$$

Two conditions are possible:

1. $E_c < i_pR_k$ so that grid is negative with respect to cathode, then

$$e_g = E_c$$

and

$$e_{p3} = E_b - i_{p3}R_L$$

$$= \frac{E_b - (E_b + uE_c)\,R_L}{R_p\left[1 + \dfrac{R_L}{R_p} + (1 + u)\,\dfrac{R_k}{R_p}\right]}.$$

2. $E_c > i_p R_k$ so that grid is zero with respect to cathode, then

$$e_g = i_p R_k$$

and

$$i_{p3} = \frac{E_b - i_p R_L - i_p R_k}{R_p},$$

$$= \frac{E_b}{R_p\left(1 + \frac{R_L}{R_p} + \frac{R_k}{R_p}\right)},$$

$$e_{p3} = \frac{E_b - (E_b R_L)}{R_p\left(1 + \frac{R_L}{R_p} + \frac{R_k}{R_p}\right)},$$

$$= \frac{E_b R_k}{R_p\left(1 + \frac{R_L}{R_p} + \frac{R_k}{R_p}\right)}.$$

B. *Calculation of maximum negative grid voltage* C_g.

1. For first condition in A

$$e_{g1} = e_{g3} - i_{p3} R_L$$

2. For second condition in A

$$e_{g1} = E_c - \frac{(E_B + uE_c) R_L}{R_p\left[1 + \frac{R_L}{R_p} + (1+u)\frac{R_k}{R_p}\right]}.$$

In the interval when one tube is not conducting, its grid voltage is

$$e_g = E_c - (E_c - E_{g1}) \exp (t/R_{g1}C)$$

where t is measured from the time of maximum negative voltage e_{g1}. Under the assumptions, the cutoff grid voltage will be

$$e_g = \frac{-E_b}{u}$$

hence for half-period $T/2$

$$\frac{-E_b}{u} = E_c - (E_c - e_{g1}) \exp(-t/2R_{g1}C)$$

or

$$\exp(-t/2R_{g1}C) = \frac{E_b}{u} + \frac{E_c}{E_c - e_{g1}}$$

$$= \frac{uE_c}{E_b} + 1\,\frac{uE_c}{E_b} - \frac{e_{g1u}}{E_b}$$

$$T = 2R_{g1}C \ln\left(uB - \frac{\mu e_{g1}}{E_b} \,/\, uB + 1\right).$$

The curves of Figures 15 to 18 are experimental as obtained on a multivibrator using 2 6J5 tubes. The frequencies under given operating conditions are predictable to about 10 per cent using the approximate formulas developed in the preceding text and the values of the tube characteristics as given in the tube manual. The approximate formulas do not consider variations in tube characteristics with plate voltage.

Sawtooth Generator

To produce a frequency change of sawtooth character in the output of the positive bias multivibrator, its positive grid is supplied with the voltage output of a sawtooth generator. This voltage output must be extremely (within $\pm$ 0.1 per cent) linear with respect to time, i.e., exhibit a constant rate of voltage change with respect to time. The importance of a linear sawtooth generator output is appreciated by consideration of the fact that in QLA-1 output of the positive bias multivibrator changes 1 c in frequency for each 3.5-mv change in applied positive bias, and the full sawtooth excursion is 42 v. Any deviation from a constant rate of change in the sawtooth generator output results in a corresponding deviation from constant rate of frequency change in the output of the multivibrator. The effect of any deviation from true linearity in the output of the multivibrator is to change range indication of the FM system because the range scale on which the system is set is dependent for its validity on the rate of change of frequency in the transmitted signal. The change in indicated range is directly proportional to the deviation in rate-of-change of frequency.

A source of long-period nonlinearity in the sawtooth generator lies in the condenser across which the sawtooth is developed. The condenser should be as free of leakage and soakage as possible; i.e., assuming a constant charging current, the rate of voltage change across the condenser must be constant.

Further, the output of the sawtooth generator should be as free as possible from modulation (ripple) of any kind. Two possible sources of modulation, and the paths by which it may infect the sawtooth generator output, are as follows.

1. Ripple may occur in the output of the regulated power supply. In QLA-1 it has been found desirable to keep the 120-c component below 2 mv since more than 50 per cent of such component is directly applied to the sawtooth generator circuit through the supply divider.

2. Ripple induced by the VSO itself, reflected

through the plate supply, and coupled as described in (1) to the sawtooth generator circuit may be present. In QLA-1 a brute force filter in the plate supply of the VSO reduces this type of modulation to a tolerable value by isolating the power supply from regenerative feedback of the VSO.

Physical arrangement of the components of the sawtooth generator circuit should be such as to avoid wiring capacitance coupling to other circuits in the system. The constant charging circuit in the sawtooth generator must pass current at a constant rate to the condenser across which the sawtooth voltage is developed. The charging current is controlled by the constant current characteristic of the pentode tube aided by cathode degeneration.[16]

The circuit which couples the output of the sawtooth voltage generator to the VSO must present a very high impedance to the sawtooth to prevent loading. A cathode follower stage fulfills this requirement in a general way, and care should be exercised to see that it is linear throughout its full operating range.

POWER SUPPLY REGULATION

Since the sawtooth frequency-modulated oscillator [FMO] is primarily a voltage sensitive oscillator, its overall stability depends to a great extent upon stability and regulation of its power supply. This supply should be capable of maintaining a constant d-c output in spite of fluctuations ($\pm$ 15 volt) in the 115-volt a-c supply line and in spite of variations in the load imposed on it. It should present a very low impedance to frequencies from zero to a frequency higher than that of the transmitted signal. The high frequency-impedance requirement is imposed by the oscillator itself and arises from the fact that any modulation of the d-c supply appears as frequency modulation in the FMO output to the detriment of the clarity of the signal.

BLANKER-SYNCHRONIZING CIRCUIT

Since the multivibrator is a voltage sensitive oscillator, all voltage changes and pulses introduced into its circuit cause a proportional change in the frequency of its output. In recycling, a sawtooth generator impresses a large, steep wave-front pulse on the grids of the multivibrator. The resulting violent frequency change creates a loud disturbance in the receiver of the FM system. (See Section 3.2.3.)

To eliminate this disturbance the output of the FMO during the recycling period must not be permitted to enter the receiver by transmission through the water nor by injection into the first detector. Current practice effects a cutoff of FMO output just prior to the beginning of the recycling period by means of a separate blanker circuit. The blanker circuit action in turn recycles the sawtooth, and, once the recycling is completed, restores FMO output at operating level. (See Figure 18, Chapter 5 for Blanker Circuit in QLA-1.)

2.2.3 Driver Amplifier

The design of the driver amplifier has so far presented no unusual difficulties. In QLA-1 equipment, the driver amplifier-projector combination delivers an equivalent sound pressure in the water of approximately 110 db above a dyne per sq cm at 1 meter. Levels much less than this result in unreliable performance. The usual criteria apply.

1. The output impedance of the driver amplifier should match the soundhead as closely as possible.
2. The frequency response of the amplifier should be uniform within 1 db through the frequency band used.
3. The total harmonic distortion introduced by the amplifier should be less than 5 per cent.

2.2.4 Soundhead

The design requirements for both projector and hydrophone sections as well as for the soundhead as a whole are covered in considerable detail in Section 6.3.

2.2.5 Receiver

Although the design of a receiver for an FM system is a relatively straightforward prob-

lem, it is complicated by certain considerations as follows.

1. Adequate discrimination against all but certain desired frequencies.

2. Development and detection of a difference frequency obtained by heterodyning a relatively weak echo with the transmitted signal in the presence of relatively high voltages arising from leakage (crosstalk) between projector and hydrophone.

3. Establishment of high sensitivity (to relatively weak echoes) while maintaining a high signal-to-noise ratio.

4. Development of a main amplifier with sharply delineated frequency response.

5. Development of suitable input and output coupling networks.

Discrimination

Discrimination against all frequencies other than those of the operating band is accomplished in an FM receiver by (1) the input circuit which incorporates a band-pass filter exhibiting uniform response throughout the operating band and having sharp cutoffs at both terminal frequencies of such band, and (2) the IF amplifier, following the heterodyne detector, which incorporates a pass band of slope response to frequencies from something under 100 c to the upper limit of possible difference frequencies with a sharp cutoff at the upper limit.

Ideally, the transducers themselves should be a part of this discriminatory circuit, exhibiting a response which falls off sharply beyond the terminal frequencies of the operating band.

Difference Frequency Development and Detection

Owing to the high level and continuous nature of the transmitted signal, there exists at the input of any FM receiver a portion (crosstalk) of the transmitted signal which exhibits large amplitude fluctuations as well as varying phase relations.

This crosstalk is a combination of (1) direct radiation from projector to hydrophone through the structure of the soundhead and (2) signal return from very near objects through short water paths. Efforts have been made to heterodyne returning echoes with this crosstalk signal (rather than with controlled injection of a sample of the transmitted signal). Results were unsatisfactory and erratic because a relatively pure and stable local mixing signal is required to heterodyne an f-m signal. The phase variations and amplitude fluctuations of crosstalk make it unsuitable for the purpose.

Development of a suitable difference frequency has been best achieved by using a portion of the transmitted signal taken from the output of the frequency modulated oscillator as the local mixing signal. Detection of the difference frequency (particularly that arising from a weak echo) is complicated by the presence of the leakage signal described above which tends to be 60 to 70 db above the strongest echo. Every effort must be made to discriminate against it. In the present state of the art, the most satisfactory method for achieving this discrimination employs a balanced modulator incorporating a varistor. Because this particular type of modulator tends to overload in the presence of signals of slightly greater magnitude than the crosstalk signal, it has been found inadvisable to use preamplification ahead of the modulator.

Sensitivity

With transmission at a given sound pressure, sensitivity in the receiver determines the maximum ranges from which various echoes may be detected. The problem is complicated, however, by the presence of reverberation and noise from which the signal must be differentiated (signal-to-noise and signal-to-reverberation ratios).

In QLA-1, the sensitivity of the receiver at maximum gain is such that a signal input of 1 to 2 μv drives the last amplifier stage to full output. This requires an overall gain of the order of 140 to 150 db. A receiver employing this amount of gain must be carefully designed to provide sufficient linearity, stability, and a minimum of internally generated noise. It has been found desirable to maintain a signal-to-noise ratio of at least 6 db down at 1 μv input. In other words, internal set noise must not account for more than one-half the total output voltage associated with a 1 μv signal (echo) input.

In view of the amount of gain specified for the receiver it is obvious that the power supply must be designed carefully to prevent instability and resultant oscillation of the amplifier. An electronically regulated power supply is a prerequisite.

Magnitude of the total receiver gain in QLA requires that at least 60 db of controlled attenuation be inserted near the first stage (generally divided between the second and third stage) to prevent overloading of the early stages and to avoid the distortion which would be associated with such overloading.

AMPLIFIER FREQUENCY RESPONSE

As controlled by the inverse square law of divergence and other factors, a given target returns a weaker signal from long range than would the same target from a shorter range. For ease of interpretation of the visual information made available on the CRO however, identical targets should have reasonably equable representation regardless of the range. To approach this ideal, a system employing multichannel analysis of the output of the first detector (QLA-1) should incorporate slope amplification. In QLA-1, frequency response of the receiver increases 12 db per octave, between 500 and 2,000 c, corresponding to the inverse square law of divergence (here, the inverse fourth power of the *range*, because of two-way transmission losses).

The presence of slope amplification in the receiver requires that *all* stages be designed to attenuate frequencies sharply beyond both limits of their pass bands. Without such attenuation, a large amount of internally generated noise with high-frequency components appears in the output of the receiver.

INPUT AND OUTPUT COUPLING NETWORKS

Coupling requirements in the receiver present no unusual problems. The input network must (1) match the impedance of the hydrophone, and (2) discriminate against frequencies outside the operating band. Network losses at frequencies within the operating band should be kept to a minimum. The output network must match the impedance of its load (QLA-1 load: analyzer filters and speaker), and must have sufficient power-handling capacity to minimize distortion.

2.2.6 Analyzer

The output of the receiver is an acoustic spectrum containing all the information necessary to the determination of range (and, when oriented with the heading of the hydrophone beam, of bearing) of all sound reflecting objects within the operating range of the system.[17]

Analysis of this spectrum by means of a single filter, which by the heterodyne method sweeps recurrently through the spectrum, is not employed in QLA-1 because if the filter is narrow enough to give good range resolution, the time required for a single examination of the spectrum is prohibitive when compared to system requirements for rapid scanning of range and bearing. Since the minimum time required to activate any filter is the reciprocal of the filter width $1/fw$, the total time necessary to examine the complete spectrum F is the product of $(1/fw)$ (F/fw) or $F(fw)^2$. From the latter expression it is apparent that where fw is less than F, the time required to scan the spectrum is greater than $1/fw$, and increases as the filter is narrowed.

In the QLA-1 analyzer the spectrum is divided into several frequency bands by a number of filters (see Chapter 5). The exact number of filters in a given system represents a compromise between requirements for range resolution and practical limitations on size, cost, etc. The multifilter examination of receiver output requires a time of only $1/fw$ to scan the complete spectrum, rather than $F/(fw)^2$, and hence may be designed to provide much more rapid scanning than the single-filter heterodyning method. A disadvantage of the multifilter method is the excessive amount of apparatus necessary to achieve high range resolution in a spectrum of any considerable width, but, in the present state of the art, it is the only established method capable of analyzing rapidly a relatively broad spectrum for signals of varying amplitude and short duration.

The analyzer must average the amplitude of

the signal in each of its channels and store the information in such a manner that it may be sampled and transmitted to the indicator in proper time sequence. It is important that each filter exhibit reasonably flat response through its frequency band. A 1-db dip at the midfrequency of the lower filters is not detrimental. The filters are arranged so as to lap their neighbors at the 3-db down points. With this arrangement a signal appearing at the crossover point, although 3 db down in each filter, has its energy distributed in both filters so that the overall response is flat. Filter attenuation of frequencies outside their pass bands should be as high as possible.

Pulse Discrimination Networks

The acoustic spectrum to be accommodated by the analyzer is set by certain considerations already discussed under Section 2.2.1. These considerations determine the extent of the spectrum, what portion of it is to be analyzed, and the number, widths, and distribution of the filters. As previously pointed out, all these values are arrived at as the result of compromises best serving the purpose for which the system is intended. In those situations in which filter bandwidths are relatively wide (e.g., 75 c in QLA-1) pulse discrimination networks may be incorporated in the analyzer to limit the disturbance otherwise occasioned by external noise and reverberation.

The function of the pulse discrimination networks is to damp the response of analyzer detectors to signals of both shorter and longer duration than the wanted signals associated with the sweep of the hydrophone across the target. This is accomplished by establishing certain time constants for the RC circuits: (1) at the output of each detector whose function it is to store and average the signal in each channel and (2) in the grid return circuit of each such detector, coupled to the cathode.

In QLA-1, values of these time constants are such that the detector exhibits maximum gain in response to pulses of 300-msec duration as associated with a 12-degree hydrophone beam scanning across a target at 6 rpm. It is important to note that values of these time constants, as they determine the maximum response of the filters, must be related to rate of bearing scan, and hydrophone beam width.

Switching Arrangements

To make the information in the multichannel analyzer available to the indicator, a number of suitable methods of synchronous commutation can be used, any one of which scans the channels in a time sequence. Additional requirements which must be met by such a commutator are: (1) minimum switching transients, (2) easy and positive synchronization with indicator, (3) high-speed, stable, and troublefree operation.

In QLA-1, these requirements were met by an electronic, phase-shift-controlled switch (see Figure 37 and related text in Chapter 5).

2.2.7 Presentation of Information

Visual PPI

A number of possibilities for the visual presentation of information are discussed in Section 8.2.2. In the present state of the art, such visual presentation is made in the form of a PPI plot of the screen of a CRO. Since the visual indicator is the principal operating position it should have closely associated with it all operating controls for the entire system.

Intensity Modulation. It has been found advantageous to have the brilliancy or intensity of the trace as high as possible without burning the screen. This permits satisfactory legibility of the presentation in all but brilliantly lighted surroundings. To prevent damage to the screen from high intensity of the spot, controls should be provided to adjust the desired intensity under static (no-signal) conditions, and a form of automatic limiter provided to keep the intensity at or under a predetermined safe value even in the face of excitation of the strongest signals to be encountered under operating conditions. The circuit with which this is achieved in QLA-1 is illustrated in Figure 48, Chapter 5.

Screen Persistence. The persistence of the CRO screen in current practice provides a temporary record of the immediate past history of the echo-ranging procedure. For most applications the persistence of the screen should

roughly approximate the scanning interval of the system so that presentation may be reasonably constant.

Range and Bearing Cursors. References should be provided for interpreting the range and bearing information as it appears on the indicator. It is preferable that these be of an electronic type (see Section 8.2.2) rather than the currently used mechanical type (see Section 3.3.4) which to some degree introduce errors of parallax and other distortions of the PPI plot.

Switching Synchronization. Synchronization of the radial sweep (from center to outer edge) of the CRO with the operation of the electronic switch which consecutively selects channels from which the stored information is transferred to the screen of the CRO is accomplished in QLA-1 by the fact that the sweep rate and timing of the electronic switch is fed from the 60-c power main which also serves the indicator. This method was chosen from among a number of possibilities because it makes use of a signal which is available in both locations.

Bearing Orientation. Any suitable synchronous commutator would serve to orient the bearing trace on the CRO with the heading of the hydrophone. In QLA-1, a sine potentiometer serves the purpose.

In a system capable of sector scanning consideration must be given to the effect on bearing indication of the electrical delays arising within the system itself between the hydrophone and the indication. If the hydrophone were rotating continuously in one direction, such delay could be easily corrected, but when the hydrophone reverses, the correction applied for one direction of rotation gives rise to an error of double magnitude in the new direction.

In QLA-1, this problem has been solved by the introduction of a mechanical backlash in the rotation of the sine potentiometer. The sine potentiometer is loosely coupled to the soundhead in such a way that it lags soundhead training (in either direction) by an amount appropriate to the electrical delay occurring in the RC networks. (See Figures 46 and 47, Chapter 5.)

Aural Indication. In the present state of the art no particular problem is presented by requirements for aural indication. A commercial loudspeaker of medium fidelity and an essentially flat response is required.

2.2.8 Physical Characteristics

Navy specifications obtaining at the time of the design will control all physical characteristics of the equipment, including packaging, soundhead mounting (hoist-train mechanism, if required), type of power, centralized remote controls, and other components.

Chapter 3

EXPLORATORY DEVELOPMENT

3.1 EARLY HISTORY

FREQUENCY MODULATED sonar systems are characterized primarily by the ability to scan a given target area automatically and continuously, and to present the data accumulated on a *plan position indicator* [PPI] in the form of a radial plot.

The FM systems research and development program culminating in Navy Model QLA sonar, was initiated in the early summer of 1941, at the University of California Division of War Research [UCDWR], which at that time was under contract to the Office of Scientific Research and Development [OSRD].

3.1.1 Statement of the Problem

Echo-ranging equipment in use at the time work was begun on the FM systems was of the step-search sonar type commonly referred to as pinging systems.

The FM systems program sought a method of scanning the area around the echo-ranging vessel rapidly and of presenting the information accumulated in a form which could be readily evaluated by the conning officer in planning offensive and defensive actions.

In 1941, there appeared to be two possible approaches to the problem: (1) development of improved systems utilizing single pings or pulses of sound and (2) development of a new type of echo-ranging equipment based on the use of continually radiated sound.

Although the first-mentioned approach was adopted by other laboratories, UCDWR chose to follow the latter avenue of investigation. The most promising of many ideas proposed in answer to the problem came to be known as the *echoscope concept,* and was the basis for the FM system development which culminated in QLA sonar.

3.1.2 The Echoscope Concept

In attacking the problem, UCDWR went beyond the basic echo-ranging requirements of locating a target in bearing and range to envision a device which would automatically delineate the outline of the target on the screen of a cathode-ray oscillograph. It was proposed that the transmitted sound be continuous, but undergo a slow frequency modulation of cyclical character, perhaps a sawtooth frequency-time pattern. Modulation was necessary in order that a distinguishable difference frequency would exist between the signal being transmitted and the echo being received at any given instant.

It was further proposed that the receiver be arranged to select echoes returning from one desired range only. Assuming a slow, sawtooth frequency modulation of the transmitted sound, the echo appearing at the receiver should lag behind that of the transmitted signal by the time required for the signal to travel to the target and back. This time lag would produce a continuous difference frequency of monitorable quality, suitable for range indication.

It was proposed that scanning in azimuth be accomplished in the usual mechanical manner or by the use of an acoustic grating such as the Bell Telephone Laboratories supersonic prism. (See Sections 3.3.1 and 4.2.)

An echo-ranging system producing a continuous echo would be able to accumulate and present range and bearing information much more rapidly than pinging systems. This accumulated information could be portrayed on a CRO screen and further monitored by a loudspeaker.

The ultimate system to be developed within the broad framework of the echoscope concept would scan all the water around the echo-ranging vessel continuously, automatically, and systematically, and present information derived from this scan rapidly and continuously.

3.1.3 Implementing the Concept

Since personnel were not available to develop the proposed system at a pace fast enough to meet the Navy's needs, it was decided to approach various manufacturers already established in the field of commercial electronics and

to enter into contract with them for the construction of equipment. In the summer of 1941 a series of meetings was held between members of the UCDWR and representatives of the Brush Development Company. Out of these meetings grew a set of desiderata[18] governing the construction of an Echoscope echo-ranging system.

Based on these desiderata an order was placed for a complete FM echo-ranging device consisting of a frequency-modulated oscillator operating at 36 to 48 kc, a driver amplifier to raise the level of the *frequency modulation oscillator* [FMO] output to the point that it could drive a crystal projector, a suitable hydrophone, and a receiver with an i-f frequency of 6 kc. The equipment was to be packaged ready for installation aboard ship.

During the construction of the system early experimental tests indicated that adequate linearity and stability of the *sawtooth-modulated oscillator* [SMO] would be difficult to obtain. However, design had been frozen by this time, and rather than attempt to make changes in the Brush unit it seemed advisable to order from other manufacturers sawtooth-modulated oscillators designed to be interchangeable with the oscillator in the Brush system. Orders were placed with the Bell Telephone Laboratories, Inc., New York City, and with the Hewlett-Packard Company, Palo Alto, California, for such equipment. In each case the contracting firm was given a free hand in design, after having been fully advised of the problems involved.

In addition to making arrangements with outside manufacturers for certain systems and components, the UCDWR immediately undertook a full-scale development program in its own laboratories.

3.1.4 Exploratory Background

Prior to UCDWR's investigation in the field little had been done with *continuously radiated* frequency-modulated sound in underwater echo ranging. So little was known in this field that a great amount of spadework was necessary to determine what type of gear would best fit the requirements. As the facilities and personnel at UCDWR expanded a number of investigations were conducted concurrently. At times four or five complete systems were being used simultaneously to investigate various aspects of the problem. Because of the multifarious nature of the developmental work, it seems best to break down this report of the exploratory development into two main classes. Accordingly, the material has been organized arbitrarily under the following headings: (1) transmission of sound, (2) accumulation and presentation of information. In the following text the developmental steps peculiar to each classification are examined individually.

Nomenclature

Any discussion of development, of course, involves the names of equipment units which served as tools. In order that these may be more readily understandable the following brief explanation is offered. The Brush Development Company built the equipment called for in the initial contract under the name of *selective echo-determining equipment,* but this name was almost immediately dropped in favor of a shorter term, *Echoscope.* In midsummer of 1942, the term *Cobar,* for continuous bearing and range, was invented. Cobar was used for about two years to cover a total of eight systems. A modification of Cobar was known as Subsight and under this designation six systems were constructed and tested. A second special modification of Cobar designated *Pribar* involving the use of the Bell Telephone Laboratories supersonic prism (Mason prism) was used to cover the construction of three systems.

Subsequently three systems were built under the designation of *Fampas,* standing for frequency and mechanically plotted area scan. Following Fampas, in an effort to bring the designation more closely in harmony with standard Navy procedure, a number of systems were built under the name of *FM sonar.* The final designation, as of the date of this report, is *QLA sonar.* Examination of the Sequence Graph of FM Systems Development (Figure 1) helps to make clear the chronological sequence and relationship of the various investigations conducted under the foregoing designations.

3.2 TRANSMISSION

Under this heading are considered all aspects of the problem which are concerned with the development and modification of the signal within the system itself and its transmission into the water. The general subject is discussed in connection with the various functional components involved: *frequency-modulated oscillator* [FMO], drive amplifier, and projector.

3.2.1 The Frequency-Modulated Oscillator

The frequency-modulated oscillator is the heart of any FM system, controlling as it does so many of the system's parameters. As used in this report, the term sawtooth-modulated oscillator refers to a circuit consisting of a power supply, a sawtooth generator, and a voltage-sensitive oscillator [VSO]. The goal has been to produce a frequency-modulated oscillator whose output would be linear with respect to time within tolerances of only ± one-tenth of one per cent. In addition to being linear, the signal must be stable. Its stability depends upon a power supply which must withstand varying a-c line voltages in the nature of 115 ± 15 volts and must also present extremely low impedance to frequencies from below 1 c up to 60,000 c.

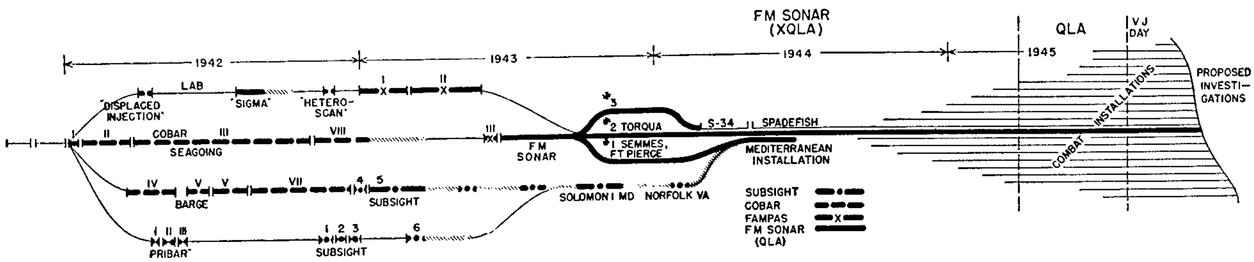


FIGURE 1. Sequence graph of FM systems development.

FMO OF THE BRUSH DEVELOPMENT COMPANY

The echoscope of Brush Development Company was delivered to UCDWR in December 1941. Its FMO consisted of a sawtooth generator of the constant current charging type in which the rate of charge was controlled by a pentode tube. The condenser was discharged by a thyratron gas tube. The output voltage of this sawtooth generator was applied to the grid circuit of a vacuum-tube reactance modulator which in turn governed the frequency of a 450-kc inductance-capacity (LC) tuned oscillator. The output of the oscillator was fed to a heterodyne detector where it was mixed with the output of a 408-kc crystal control oscillator. This arrangement produced a 42-kc ± 6-kc difference frequency. As had been suspected during its construction this FMO proved so nonlinear that its use in an echo-ranging system was impossible. Subsequent tests of the balance of the echoscope system using other oscillators proved that the Brush echoscope,[18] except the FMO, met the requirements of the original desiderata.

FMO OF THE BELL TELEPHONE LABORATORIES, INC.

The Bell Telephone Laboratories FMO, ordered in October 1941, was of the same type as the Brush Development Company FMO, but incorporated certain electronic correction circuits in an attempt to bring the linearity of the FMO up to the rigid standards required.[18]

Although the oscillator section appeared to work well the d-c amplifier control circuits were so unstable that the equipment could not be operated for a long enough period of time to make a satisfactory test.

MECHANICALLY ROTATED CONDENSER FMO

UCDWR made an early attempt to develop an oscillator using mechanically rotated condensers to produce frequency modulation. The equipment comprised two variable speed motors opposing each other through a mechanical differential. The output of the differential monitored by a modified Dodge speedometer rotated two diametrically opposed condensers mounted

on a common shaft. Sawtooth modulation was obtained by switching alternately from one condenser to the other, twice per revolution.

Electronically the oscillator was a simple feedback circuit with the variable condensers forming part of the total capacity. The plates of the condensers were shaped and adjusted to give a straight-line frequency characteristic to the unit. The device failed to produce a sawtooth modulation of sufficient linearity, because of difficulties encountered in providing a uniformly varied rate of capacitor rotation (ranging from 2 to 60 rpm) which were still unresolved at the time the Hewlett-Packard electronic oscillator became available. Subsequent developments were based on the electronic oscillators only.

FMO of the Hewlett-Packard Company

The device of the Hewlett-Packard Company, ordered in November 1941, generated the desired output frequency directly by the use of the positive bias multivibrator instead of using the reactance tube technique. The Hewlett-Packard FMO[15] provided a reasonably linear signal and behaved in a predictable manner.

The Hewlett-Packard oscillator was incorporated in a system designated as Cobar Mark II (see Chapter 4). With it the first echoes from submerged targets were obtained. Ranges up to 1,000 yd on large targets were occasionally achieved even with the crude projector-hydrophone assemblies then available.

Although modifications were subsequently made in the Hewlett-Packard circuit, present frequency-modulated oscillators used in QLA echo-ranging equipment are patterned after Hewlett-Packard's original design.

UCDWR Investigations

While the Hewlett-Packard oscillator had been workably linear, it was realized after early tests that it did not approach the ideal tolerance of only $\pm$ one-tenth of 1 per cent. Development of an oscillator of increased linearity was hampered by the fact that techniques had not yet been established for checking the linearity of an FMO accurately, nor was it thoroughly understood what parameters within the FMO itself controlled linearity. A program of research to answer these questions was projected, but in the meantime a period of blind experimentation ensued which resulted in a UCDWR oscillator designated as the RO-1.[18] The RO-1 proved to be considerably more linear than any previous unit. For some time subsequent systems were constructed as copies of the RO-1 oscillator in order to preserve the degree of linearity which it offered.

Concurrently, experimental work was undertaken in which the sawtooth generator and the voltage sensitive oscillator components of the RO-1 were interchanged with their counterparts in previous FMO models. Tests of these varying combinations developed the fact that the constant current pentode control-type of sawtooth generator was sufficiently linear for the purpose of FM systems, and that most of the nonlinearity evinced by previous FMO models had arisen in the oscillator rather than in the generator. Copies of the RO-1 oscillator were used throughout the FM system development program for all Cobar and associated systems.

With the coming of Fampas systems, however, and their multichannel method of analyzing the frequency spectrum (in indicating range), the requirements for linearity in the signal materially increased.

The measurement program which had been projected earlier now culminated in the identification and determination of those characteristics of an FMO which were responsible for its linearity. From this study, a family of curves was developed which made it possible to set up design parameters which would produce acceptable linearity in the FMO for any chosen band of frequencies. The circuit components in the FMO of QLA-1 are based on the parameters obtained as the result of these studies which were given in detail in Section 2.2.

3.2.2 Checking the Linearity of the FMO

Corollary to the theoretical determination of the maximum permissible deviation from linearity in the FMO as one-tenth of 1 per cent arose the problem of checking linearity within this degree of accuracy to determine whether

or not design considerations had been satisfied.

Nonlinearity affects Cobar systems (and others using a single band-pass receiver) by introducing a warble which makes the two tones arising from the difference frequencies "images" difficult to compare and, hence, makes it difficult to focus the system on a specific target. If warbling (nonlinearity) is severe the difference frequency wanders in and out of the single filter and decreases the signal-to-noise ratio and consequently hampers target identification.

In systems employing multichannel analysis nonlinearity results in a frequency shift which brings the target indication into a different channel than the one indicative of true range.

Efforts to check the linearity of the FMO were early divided into two parts: (1) checking the linearity of the sawtooth generator and (2) checking the linearity of the system output.

Efforts to check the linearity of the sawtooth generator were concerned with the measurement of the rate of voltage change across sawtooth condenser. A method using a differentiating network was found unsatisfactory because of the disturbance occasioned by flyback (condenser discharge) in the frequency-modulated signal. An attempt to compare the sawtooth waveform with a low-frequency sine wave on a *cathode-ray oscilloscope* [CRO] in which exactly equal spacing between the consecutive maxima of the sine wave would denote perfect linearity, was found to be inherently too inaccurate for the purpose. The same fault was found with an attempt to check the linearity of the sawtooth generator by impressing the sawtooth voltage waveform on a high-speed recording oscillograph and laying out an evenly divided (time) base line against which the slope of the sawtooth could be measured.

One method which did work within its field was developed for checking the constant current portion of the sawtooth generator and was a simple current measurement. A microammeter was inserted in the cathode circuit of the pentode with a bucking voltage in parallel to balance out the constant part of the current.

Before any completely satisfactory method for checking the linearity of the sawtooth generator was devised, previously mentioned experiments conducted with the RO-1 FMO indicated that the sawtooth generator itself was not a serious source of nonlinearity in the output of the FMO. Further studies of linearity were accordingly centered on the function of the voltage-sensitive oscillator rather than that of the sawtooth generator.

Hewlett-Packard Signal Simulator

In developing the FMO previously mentioned the Hewlett-Packard Company devised its own method of checking its linearity with a device which it designated as a signal simulator.

Figure 2 is a block diagram of the simulator, which functions as follows.

The supersonic output of the oscillator is first fed into a frequency divider circuit whose output is at all times exactly one-ninth of the frequency it accepts from the oscillator. This one-ninth frequency signal may then be recorded on an acetate disk in the conventional manner. Lagging the recording head by 1 or more revolutions of the acetate disk is a pickup head. The signal from the pickup head lags in time (consequently in frequency) behind the signal being recorded. A sample of the signal being recorded is heterodyned with the signal of the pickup head to produce a difference frequency which is filtered, amplified, and fed to a loudspeaker. By measuring the constancy of this difference frequency an accurate check may be obtained on the linearity of the sawtooth-modulated oscillator.

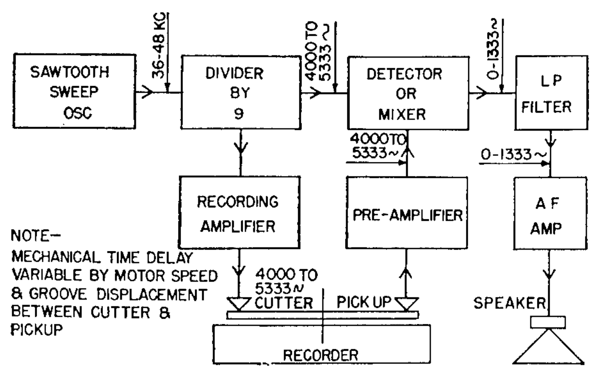


FIGURE 2. The Hewlett-Packard signal simulator, block diagram.

The principal source of error in this measuring device lay in the fluctuation in the rotation

rate of the turntable. Another drawback was that the division by nine made the test procedure one-ninth as sensitive as it would have been at the original frequency, and amounts of nonlinearity just detectable by ear on the testing device became intolerable under actual operating conditions because they were nine times as large.

The signal simulator was used for some time to provide checks on various oscillators and for the purpose of demonstrating FM systems out of the water but it was outmoded when the development of FM sonar progressed to the point at which dependable evaluations could be made by the use of a water-path delay and a test target.

Controlled Targets

Obviously one of the best ways to check linearity of any FM system is with the system itself operating over a water path. To make such a procedure successful it is necessary to have a target which may be depended upon to return clear, strong echoes (above reverberation).

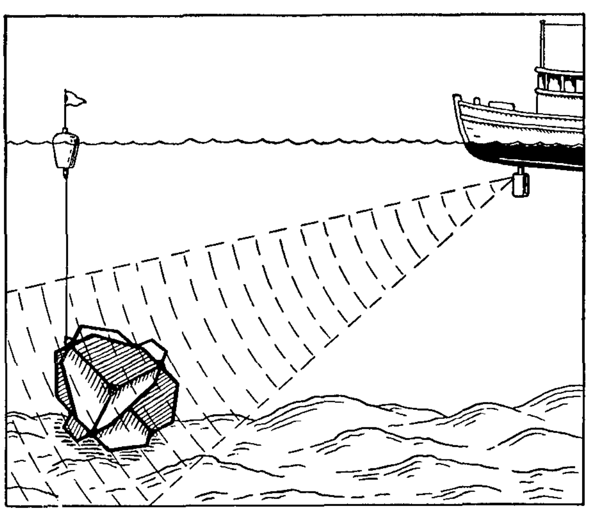


FIGURE 3. Checking linearity with controlled target.

In seeking such a target attempts were first made to use a 10-ft diameter steel sphere which proved too difficult to handle. A 3-ft diameter steel sphere did not have sufficient echo strength. It was found that a 6-ft triplane had an echo strength noticeably better than that obtained with a 10-ft sphere and had the additional advantage of being much more easily handled. Satisfactory echoes were obtained with this device at ranges up to 1,200 yd with the system known as Cobar Mark III.

The technique for measuring the linearity of a system with a triplane is as follows: The system itself (including soundhead) is mounted on a pier or other stationary location. The triplane is anchored at a depth of approximately 30 ft, and at a distance of 200 yd or more from the echo-ranging system. The triplane is buoyed so that the soundhead may be trained directly and accurately on the triplane. Under these conditions it is possible to get an echo over a water path of known length. The echo is monitored through a loudspeaker and the constancy of pitch of the echo tone is a test of linearity in the system. See Figure 3 for a diagram of the test procedure. While this procedure gave a workable test of the linearity of a system, it depended entirely on the skill of the operator in detecting variations in pitch.

With the development of Fampas systems it became possible to utilize the same basic technique, but to measure linearity in terms of cycles per second. By maintaining a 1/1 Lissajous on the CRO screen against the output of a control oscillator the degree to which the control oscillator had to be adjusted to maintain the 1/1 Lissajous was an indication of the amount of nonlinearity in the system. Since this technique utilizes a controlled target and a delay water path, it suffers from whatever variations may occur within the water path itself.

Artificial Water Path

In an attempt to eliminate the variables which might arise from the use of a changing water path, work was initiated in July 1944 on a delay circuit to serve as an artificial water path.

In form the device was a mechanical, nondispersive lag line constructed of coil springs of small pitch and small diameter. See Figure 4. In test models the attenuation in such springs proved to be too high and the device was never perfected. The tests indicated, however, that a lag line utilizing springs coiled from wire of approximately 1 mil in diameter produced the

desired time delay without excessive attenuation. Further investigation aimed toward the development of an artificial water path for demonstration and production testing of FM systems is planned.

PLOTTING MEASUREMENTS

Another field of investigation had been concerned with checking the linearity of the *voltage-sensitive oscillator* [VSO] as differentiated from the sawtooth generator by plotting its frequency change as a function of the voltage change applied to its grids. Early attempts failed because equipment of sufficient accuracy

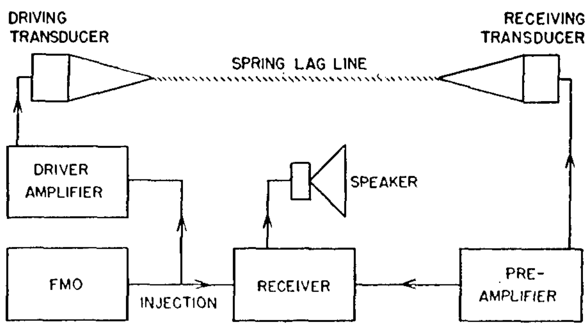


FIGURE 4. Artificial water path delay circuit.

to check deviations from linearity of the order of ± one-tenth of 1 per cent was not available.

Late in 1943 a calibrated potentiometer of sufficient accuracy became available to make it possible to change the voltage applied to the grids of the multivibrator by extremely small and accurate increments. The output frequency of the multivibrator was compared to a secondary frequency standard. By this means it was possible to check the linearity of the multivibrator within ± 0.1 per cent; but the procedure was so tedious that it was not adaptable to production testing of FM systems.

3.2.3 Blanking

In all FM systems to date, it has been found necessary to cut off the output of the frequency-modulated oscillator (both transmission into the water and injection into the receiver) during the short period when the sawtooth signal returns to its initial frequency. This procedure is termed blanking.

Blanking is necessary because of the electrical and acoustical disturbances set up within the system by the abrupt but finite frequency change during the flyback period.

Electrical disturbance is of short duration, occurs in the receiver, and is introduced by the injection flyback. The acoustical disturbance is of longer duration, is a type of reverberation, and arises from the fact that the finite, though steep, slope of frequency change during flyback makes the system responsive to targets at very short ranges (within a few feet) at the instant of flyback. This acoustical disturbance arises from the flyback occurring in the transmitted signal.

The problem was to devise a blanking period which exactly coincided and exactly masked the flyback period of the transmitted signal.

The first blanker consisted of a discriminator circuit tuned very close to the end of the sweep upward from 36 kc to 48 kc. (FM systems employed an upswept sawtooth at that time.) The discriminator circuit was made frequency dependent and was tuned to about 47½ kc. When the sawtooth slope of the VSO reached this frequency the discriminator developed a negative voltage. The negative voltage biased one of the amplifier tubes of the FMO beyond cutoff. Such a blanking arrangement was better than none but it had two major faults: it was frequency dependent, and it was in no way positively synchronized with flyback of the sawtooth signal. Thus, if the VSO drifted slightly (and it frequently did) the blanker failed to function as planned.

Experimental work with Cobar Mark III evolved an improved blanker consisting of a ring modulator (copper-oxide varistor) serving as a gating circuit in the output of the FMO. The gate was held open by the passage of a constant current of 5 or 6 ma. Interruption of the constant current caused the gate to close. This current was supplied by series connection of the ring modulator to the cathode of a triode. To interrupt the current a negative potential was applied to the grid of the triode, thus biasing it to cutoff so that its plate current ceased to flow. The negative potential required for

this operation was obtained from the plate of the thyratron in the sawtooth circuit, which swings negative at flyback.

Because the operation of the gating circuit was actually triggered by the flyback pulse of the FMO, synchronization had been achieved. Because the blanking action was initiated by the flyback pulse, however, blanking did not actually begin until after the sawtooth thyratron started to discharge. This left the initial portion of the flyback period still unblanked.

In an attempt to develop an anticipatory blanker, a circuit was evolved which utilized a second thyratron (in addition to the one in the sawtooth generator) to generate the blanking pulse. This second thyratron was so connected that it would be fired by the output of the sawtooth generator as it approached the end of its sweep. The firing point could be adjusted to occur as close to the end of the voltage change as was desired. The heavy current surge at the time of firing of the second thyratron created a negative pulse on its plate which was used to close the ring modulator gating circuit in the output of the FMO.

Tests of the anticipatory blanker brought out the fact that when the blanker thyratron was set close to the end of the sweep (in order to keep blanked time to a minimum), the minute variations from thyratron to thyratron sometimes resulted in the sawtooth thyratron firing before the blanker thyratron, thus leaving part of the flyback unblanked. The situation could have been corrected by setting the blanker thyratron to fire earlier, but this would have increased the blanked time and was considered undesirable. In effect some of the synchronization had been lost by this new arrangement. An additional disadvantage lay in the fact that the blanker portion of the FMO now represented a considerable number of extra components. During work with Fampas and FM Sonar Model I, Nos. 1 through 4, further modifications were made in blanking techniques which eliminated these two disadvantages.

Compactness was achieved by using a balanced push-pull type amplifier in the FMO output. With this type of amplifier the negative pulse from the blanker thyratron was applied to the center tap of the transformer feeding the grids of the push-pull output tubes, thus driving them to cutoff at the time of flyback. In this arrangement this stage performs the functions of output amplifier as well as those of a gating circuit, eliminating the ring modulator and triode associated with it.

To insure that the sawtooth thyratron would not fire before the blanker was activated, it was arranged to fire the sawtooth thyratron with a positive pulse generated by the blanker action of the output stage. This was accomplished by feeding the center tap of the plate side of the push-pull output transformer through a dropping resistor. When the tubes were driven to cutoff by a negative pulse, a positive pulse appeared at the center tap of the push-pull plate winding of the output transformer. This pulse, suitably shaped by *RC* networks, was then applied to the sawtooth thyratron causing it to fire. Thus, in effect, the blanking mechanism recycled the sawtooth instead of the sawtooth triggering the blanking circuit. This final technique is in use on QLA-1 and seems to answer the blanking problem satisfactorily.

3.2.4 Transmission Frequency

At the beginning of the FM systems development program the transmission frequency of 36 to 48 kc was selected because it was above the operating bands of then existing U. S. Navy equipment, and was believed to be outside the bands used by enemy underwater sound equipment. Thus, the 36- to 48-kc band was thought to have dual advantages: (1) noninterference with our own existing echo equipment and (2) security in some degree from enemy detection.

The 36- to 48-kc band has been utilized in the majority of FM systems to date with a few experimental exceptions and a few exceptions of convenience.

Pribar units (see Chapter 4) operated in the 18- to 24-kc band because they utilized the Bell Telephone Laboratories' supersonic prism as a hydrophone, and the prism had been designed for that frequency band.

The proposition has been repeatedly advanced during the FM system development that a lower operating band would through less attenuation

of sound in water increase maximum ranges. To explore the situation Cobar Mark VI was so designed and constructed that it could be operated on either of two bands: 18 to 24 kc or 36 to 48 kc. Cobar Mark VII also made the 18- to 24-kc band available for experimental purposes. At one time Cobar Mark VII and Cobar Mark III (the latter operating on the 36- to 48-kc band) were installed on the same echo-ranging vessel and operated in competition with each other. Further investigations of the frequency-range relationship were made in a small way with FM Sonar Model 1, No. 1, operating at an average frequency of 28 kc. All the comparisons mentioned above were inadequate to any definitive determination of the frequency-range relationship and only succeeded in establishing the fact that, for the systems involved in the tests, factors other than frequency were limiting on range and hence no change in operating band resulted.

During the period in which the emphasis in the FM systems development was on small-object detection, FM Sonar Model 1, No. 3 was constructed to operate on the band extending from 52 to 68 kc in the belief that this higher frequency (and consequent shorter wavelength) would give better definition on small objects.

Again tests were inconclusive, and although some improvement in definition of small objects was noted, it did not seem sufficient to merit a change in operating band with all the system modifications such a change would have required.

After the one attempt at a higher operating band all subsequent systems utilized the 36- to 48-kc band until the present FM system QLA-1 in which the frequency was changed to 36 to $46\frac{2}{3}$ kc only to accommodate temporarily inadequate projectors. In projected production models of FM systems the frequency band will undoubtedly again become 36 kc to 48 kc.

3.2.5 Driver Amplifier

Power requirements of FM systems have never been such as to make the design and construction of a satisfactory driver amplifier difficult. Various drivers have been used with the various developmental systems and in each case were designed to meet the requirements peculiar to the purpose for which the system was intended. See data sheets in Chapter 4 for details on drivers used with developmental systems, and Chapter 5 for driver amplifier of QLA-1.

3.2.6 Projector

Up to the time it goes into the water, the power developed in an FM echo-ranging system is in the form of electrical energy. A device known as a transducer, or soundhead, is used to convert electrical energy into sonic energy as the power is transmitted into the water. (The procedure is reversed as the echo returns to the hydrophone.) At present the two best transducers are of either the magnetostriction type or the piezoelectric crystal type.

Magnetostriction units generally have such a high Q that they are not particularly suitable for use with FM systems which operate over a relatively wide band of frequencies. For this reason the piezoelectric transducer is employed with FM systems.

At the inception of the FM systems program the field of piezoelectric transducers was relatively undeveloped and the primitive state of the art handicapped FM systems development throughout its early stages.

Earlier underwater echo-ranging systems had used a single crystal motor for both transmission and reception. This was possible because of the intermittent character of the transmission, but separation of the projector and hydrophone seemed to promise better results with the continuously radiated sound of FM systems. The only transducer then readily available was a unit known as the C13 which was being produced by the Brush Development Company. In comparison with the transducers used today, it was very small, about 4 in. by 4 in., with a thin Phosphor-bronze diaphragm to which X-cut Rochelle salt crystals were cemented. The C13 was air-filled.

To increase the limited power-handling capacity of the C13 several units were connected

either in series or parallel as a single projector.

The parallel connection proved unsatisfactory because the impedances of the individual units varied erratically with temperature and with power applied. Under such conditions one unit was likely to consume all the power applied to the group and so destroy itself in a matter of seconds under the continuous operation required by FM.

The series connection proved equally unsatisfactory because of the high impedance presented to the driver.

The previously mentioned fact, that impedance of the C13 was a function of both of its internal temperature and of the amount of current passing through it, made impedance matching and frequency response equalizing networks almost impossible to design and of doubtful advantage.

Early attempts to improve the stability of C13 units and to make possible better matching to the driver amplifier were embodied in a transducer known as the C26. The C26 consisted of four crystal motors similar to C13, mounted on a common backing plate and contained in a common case. One-half of each crystal motor was connected to the high-impedance secondary of its own transformer, eight transformers in all, and the low-impedance primaries of these transformers were connected in series to the driver amplifier. This arrangement improved the stability of the projector, because, with the primaries connected in series, no one crystal motor could take all the power applied to the group. Projectors of this type were used for all Cobar systems, but were seriously limited in the amount of power they were able to put into the water. However, the C26 type of projector did make it possible to achieve ranges of 1,000 to 1,200 yd as compared to ranges of 200 to 300 yd which had been the maximum possible to those systems employing the C13 projectors.

Toward the end of the experimental work with Cobar systems, the newly established Transducer Laboratory at UCDWR began supplying all transducers for FM systems, and details of this work are found in Section 6.1.

It is sufficient to note here that since Y-cut Rochelle salt crystals are relatively temperature independent they were substituted for the temperature dependent X-cut crystals with a consequent improvement in projector performance. Projector design progressed rapidly until the Y-cut Rochelle salt crystals were themselves a limiting factor in projector performance. With the introduction of Z-cut ammonium dihydrogen phosphate [ADP] crystals another improvement in projector performance was made.

The CJJ78256 projector being used with QLA-1 exhibits a major fault in terms of system requirements. Its frequency response falls off rather sharply from 46⅔ to 48 kc instead of being relatively flat from 36 to 48 kc. It was this fault which made it necessary to establish the operating band of QLA-1 at 36 to 46⅔ kc instead of 36 to 48 kc. Its power-handling capacity (it is capable of putting into the water 106 to 110 db above 1 dyne per sq cm at 1 yd) is such that any further advance in this respect has to await the solution of the problem of crosstalk between the projector and hydrophone. This possibly entails the development of a better first detector or ultimate spatial separation of the projector and the hydrophone.

The projector stability is adequate, and work is going forward on improved matching of the driver amplifier and the projector for an improved relationship between the amount of power supplied to the projector and the amount of power put in the water by it.

3.3 ACCUMULATION AND PRESENTATION OF INFORMATION

3.3.1 Hydrophone

During the early stages of the FM system development, Brush Development Company's C13 crystal motors were used as hydrophones. Because they had not been designed for the frequency range used in the FM systems, it is not surprising that their performance was not satisfactory.

Consequently, UCDWR began construction of its own hydrophones under the designation of GA. Main advantages of the GA series of hydrophones lay in the fact that, since they

were comparatively independent of temperature (Y-cut Rochelle salt) and were relatively stable, the capacitive reactance could be largely canceled with tuning coils to give a much better impedance match to the receiver input than had been possible with C13 and C26 transducers.

Hydrophone development from the point at which UCDWR undertook the construction of its own transducers is fully reported in Section 6.2.

It is sufficient to note here that aside from the mechanical problems involved in developing a hydrophone sufficiently rugged for use under service conditions hydrophone development was primarily concerned with suppression of side lobes to improve the response pattern.

A hydrophone originally developed as the GA14Z, employing Z-cut ADP crystals and exhibiting a lobe suppression of about —26 db, is the one incorporated in the hydrophone-projector combination in use with QLA-1.

3.3.2 Scanning in Range

In all FM systems, scanning in range is concerned with analysis of the output of the system's first detector. It is in the first detector that the received echo is mixed (heterodyned) with a sample of the transmitted signal to produce a difference frequency on which all FM system range determination is based. All the early systems, Cobar and its modifications, examined the output of the first detector by means of a single filter. Fampas and subsequent systems, FM sonar and QLA sonar, utilized multiple filters to examine the output of the first detector in securing range information.

Single-Filter Examination of Output of First Detector

Although all Cobar and related systems used a single filter to examine the output of the first detector, there were five significant variations of this technique. Each of the five procedures exhibited one or more features which were important solutions of one or more aspects of the echo-ranging problem, but no one of them was versatile enough to fill all the requirements of an FM system.

Delta Cobar. In Figure 5 is plotted one sawtooth excursion of the transmitted signal together with the sawteeth representing echoes returning from targets at three different ranges. It will be noted that the echo sawteeth are displaced along the time axis by an amount proportional to their range. This displacement produces at any point along the sawtooth slope a difference frequency between the transmitted

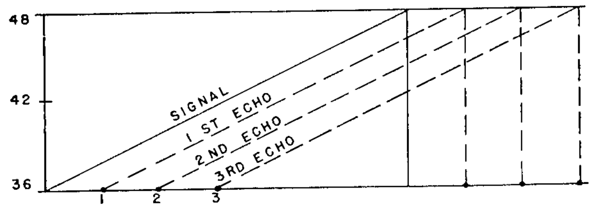


FIGURE 5. Delta Cobar operation: one sawtooth excursion and associated echoes.

signal and the echo characteristic of the range to the target from which the echo was received. The use of this difference frequency as an indication of range is common to all FM systems; Cobar systems differ from those systems

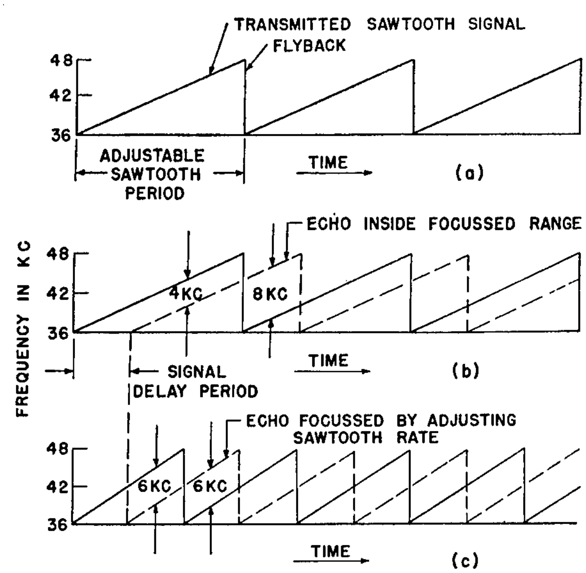


FIGURE 6. Delta Cobar operation: range determination.

employing multiple filters only in their method of examining this difference frequency.

The Delta Cobar receiver employed a single pass band 600 c wide, and centered at 6 kc for a transmission frequency band of 36 to 48 kc. The Delta Cobar method of measuring range

to a target is illustrated in Figure 6. Here *a* diagrams the transmitted sawtooth signal, *b* diagrams the difference frequency existing between the echo and the transmitted signal. It will be noted that there are alternately present within the sawtooth excursion two difference frequencies: 4 and 8 kc. Since the receiver pass band following the first detector is 6 kc ± 300 c, the difference frequency as shown in *b* is either not recognizable through the pass band or at best produces a very weak indication. To bring the echo within the comprehension of the 6-kc receiver pass band, the rate of the sawtooth modulation period is varied until the echo returns exactly halfway through the sawtooth cycle. This condition is shown in *c* where it will be noted that the difference frequency throughout the complete cycle is exactly 6 kc. The echo frequency is 6 kc higher than the transmitted frequency through one-half of the sawtooth cycle and is 6 kc lower than the transmitted frequency through the other half; but the *difference* frequency is the same throughout the entire cycle. Thus, if the sawtooth signal is perfectly linear, a steady 6-kc note is heard at the output of the receiver, and the system may be said to be focused on the target.

The length of the sawtooth modulation period was manually controlled by the operator in the Delta Cobar system by means of a dial which was calibrated for range in yards. Range scanning was accomplished in all Delta Cobar systems by manipulating the range dial (sawtooth modulation period control) slowly from a minimum to a maximum range while the projector and hydrophone were set at one bearing. Any target appearing within the field could be brought into focus by manipulation of the range dial and comparison of the tones emitted from the system's loudspeaker. Range at focus position could be read on the dial.

The procedure just described gave extremely accurate range information and made it possible once a target was brought into focus to follow it through any maneuver. One modification of the Delta Cobar systems known as Subsight (Chapter 4) utilized these advantages for fire-control purposes in antisubmarine applications.

However, this method required the operator to adjust the sawtooth period manually to a succession of ranges in searching for a specific target and was a very slow method of range scanning as compared to that available with pinging systems. Delta Cobar procedures failed to take advantage of the fact that FM operation made every target a source of continuous sound.

Displaced Injection in Delta Cobar. Injection is the term commonly used in FM systems to designate that portion of the transmitted sawtooth signal which is introduced or injected into the first detector to be heterodyned with the echo for production of difference frequencies related to range. One of the things which made range scanning such a slow operation in the original Delta Cobar procedure was the fact that it was impossible to get a focus on a target immediately after changing the setting of the range dial. The delay arose from the fact that the changed slope of the sawtooth was required to travel out to the target and return to the hydrophone before the focus could be obtained.

An attempt was made to eliminate this particular source of delay by providing a separate

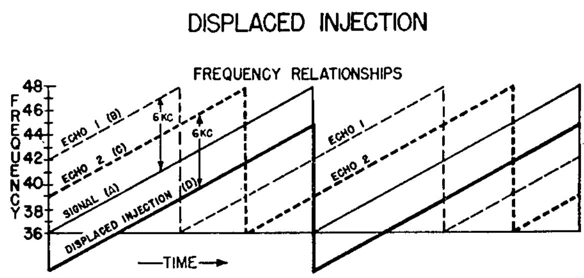


FIGURE 7. Displaced injection in Delta Cobar: transmitted signal and associated echoes.

source of injection frequency which could be shifted or displaced in relation to the outgoing signal at the will of the operator and with great rapidity. The mechanics of this displaced injection are diagramed in Figure 7 in which *a* is the outgoing signal; *b* is an echo which is in focus with the injection arising from the transmitted signal; *c* is an echo which is out of focus with the injection arising from the transmitted signal; and *d* is a displaced injection arising from a separate injection source—a displacement up or down in frequency of *d* with rela-

tion to the outgoing signal at all times maintains the same rate of change of frequency in cycles per second as the transmitted signal. Certain obvious advantages would accrue to the use of a displaced injection which was displaced horizontally in time (rather than vertically in frequency), but the circuit complication would have been considerable. In the diagram *d* has been displaced by an amount sufficient to bring it into focus with echo *c*, which had not been in focus with the injection arising from the transmitted signal *a*. With this arrangement

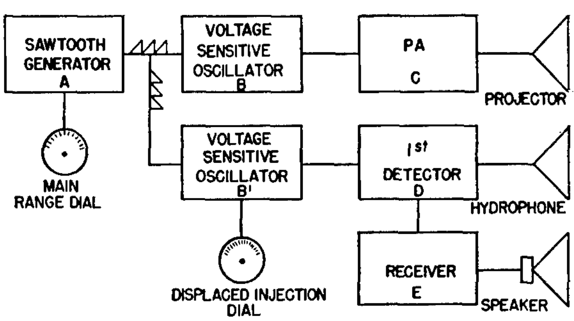


FIGURE 8. Displaced injection in Delta Cobar: system block diagram.

it was possible at any given setting of the main range dial to scan a limited range on either side of the main range. In effect, the Delta Cobar focus was given greater depth for the purpose of searching in range without sacrificing any of its accuracy of range determination once the target had been located. Figure 8 is a block diagram of the displaced injection modification Delta Cobar. Designation *a* is the sawtooth generator whose repetition rate is controlled by the main range dial. Output of *a* is fed to the voltage-sensitive multivibrator *b* whose output goes to a power amplifier and thence into the water in normal FM fashion. A portion of the output of the sawtooth generator *a* is fed into a second multivibrator *b′* which is identical in all characteristics to *b* with the exception that its frequency may be raised or lowered by means of a separate control dial. The output of multivibrator *b′* is used for displaced injection into the first detector.

The displaced injection modification of Delta Cobar suffered from one serious fault. There was always present some direct radiation from the projector at the frequency of the transmitted signal to the hydrophone and from there into the first detector. The level of this leakage signal is about 40 to 70 db higher than that of any returning echo. With signal injection this is not much of a problem since the leakage frequency differs from the injection frequency by at most a few cycles per second. As soon as a separate source of injection was used which was displaced in frequency from the outgoing signal, tones from the beats between harmonics of the leakage from the displaced injection and from the transmitted signal injection would be set up providing intermittent chirps and squeals as the oscillator swept through their bands. Harmonics of the direct beat note which caused strong interference whenever the difference between oscillators *b* and *b′* is 6,000 over *U* (where *U* is 1, 2, 3, etc.). These harmonics are generated within the detector itself and hence cannot be eliminated by conventional filtering methods.

Pribar-Special Injection in Delta Cobar. The Pribar modification of Delta Cobar was an attempt to achieve automatic rapid range scan by means of a specially modulated injection into the first detector against which the returning echo was heterodyned. Bearing indication was obtained by the use of a special hydrophone, the Bell Telephone Laboratories' supersonic prism, whose major lobe is shifted about the vertical axis (in the horizontal plane) to a degree dependent upon the frequency of the received echo. The prism swings its major lobe from −60 to +30 degrees in response to frequencies varying from 18 to 24 kc. For a complete description of this hydrophone see Section 6.2. Range and bearing information were presented on the screen of a CRO in the form of a Cartesian coordinate plot.

As indicated in the following discussion, range is determined by Pribar systems by a single filter but by means of the special injection to be described the single filter is made to scan a limited frequency spectrum, instead of being responsive to a single difference frequency as in Delta Cobar.

Figure 9 is a functional block diagram of the Pribar method of operation. Designation *A* is the regular sawtooth generator present in all

FM systems. Output of A drives the standard FM systems VSO B whose output is amplified at C and fed into the water through the projector D in the usual manner.

Another portion of the output of sawtooth generator A is fed through an inverter to a modulator tube F which superimposes on the 18- to 24-kc sawtooth an additional 20-c amplitude modulation to produce a waveform voltage as illustrated between F and B' in Figure 9. Under the impact of this waveform voltage the VSO B' produces a signal exhibiting two frequency modulations: (1) the basic sawtooth modulation sweeping the mean frequency from 19.5 to 25.5 kc once every 6 sec; (2) a 20-c modulation superimposing a 3-kc swing on the basic sawtooth. These two modulations produce a signal with the appearance diagramed between B' and first detector in Figure 9, and sweeping from 18 to 27 kc (rather than 18 to 24) as a result of the 3-kc swing superimposed on the basic sawtooth. From the hydrophone G the returning echo bearing the simple 18- to 24-kc sawtooth modulation which was impressed on the transmitted signal by VSO B is fed into the first detector where it is heterodyned with the specially modulated injection produced by VSO B' as just described. The heterodyned output of the first detector is passed through a 3-kc band-pass filter.

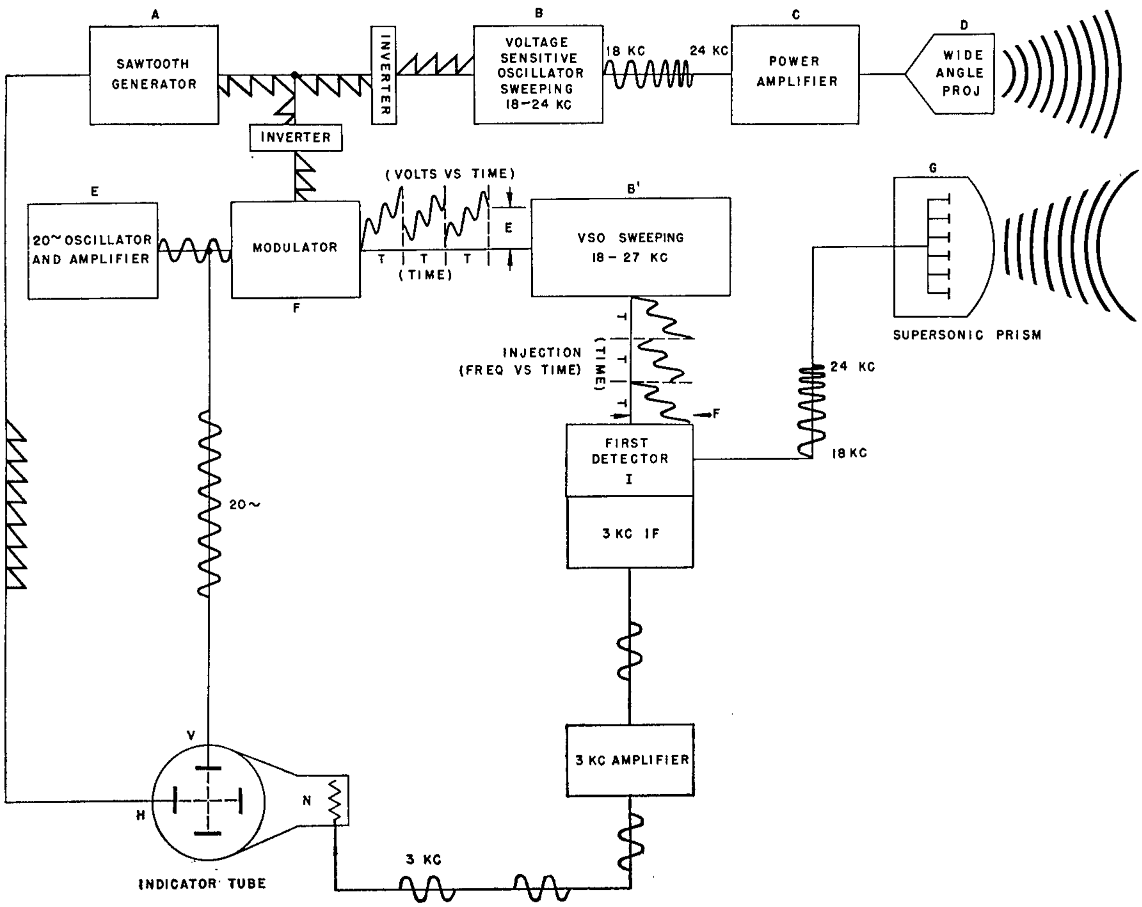


FIGURE 9. Pribar functional block diagram.

Because the transmitted signal sweeps from 18 to 24 kc once every 6 sec the system may be considered (in single-filter terminology) to be focused on a range of 2,400 yd. By reference to the upper half of Figure 10 it is seen that the echo from a 2,400-yd target differs from the transmitted sawtooth by 3 kc, and that in effect, the specially modulated injection fluctu-

ates between the nominal sawtooth frequency of the transmitted signal and the frequency sawtooth of the echo returning from 2,400 yd. Thus, the negative peaks of the injection give second, amplified, and appears as an indication on the CRO (lower half of Figure 10). Thus ranges from 0 to 2,400 yd are scanned with each cycle of the 20-c modulation.

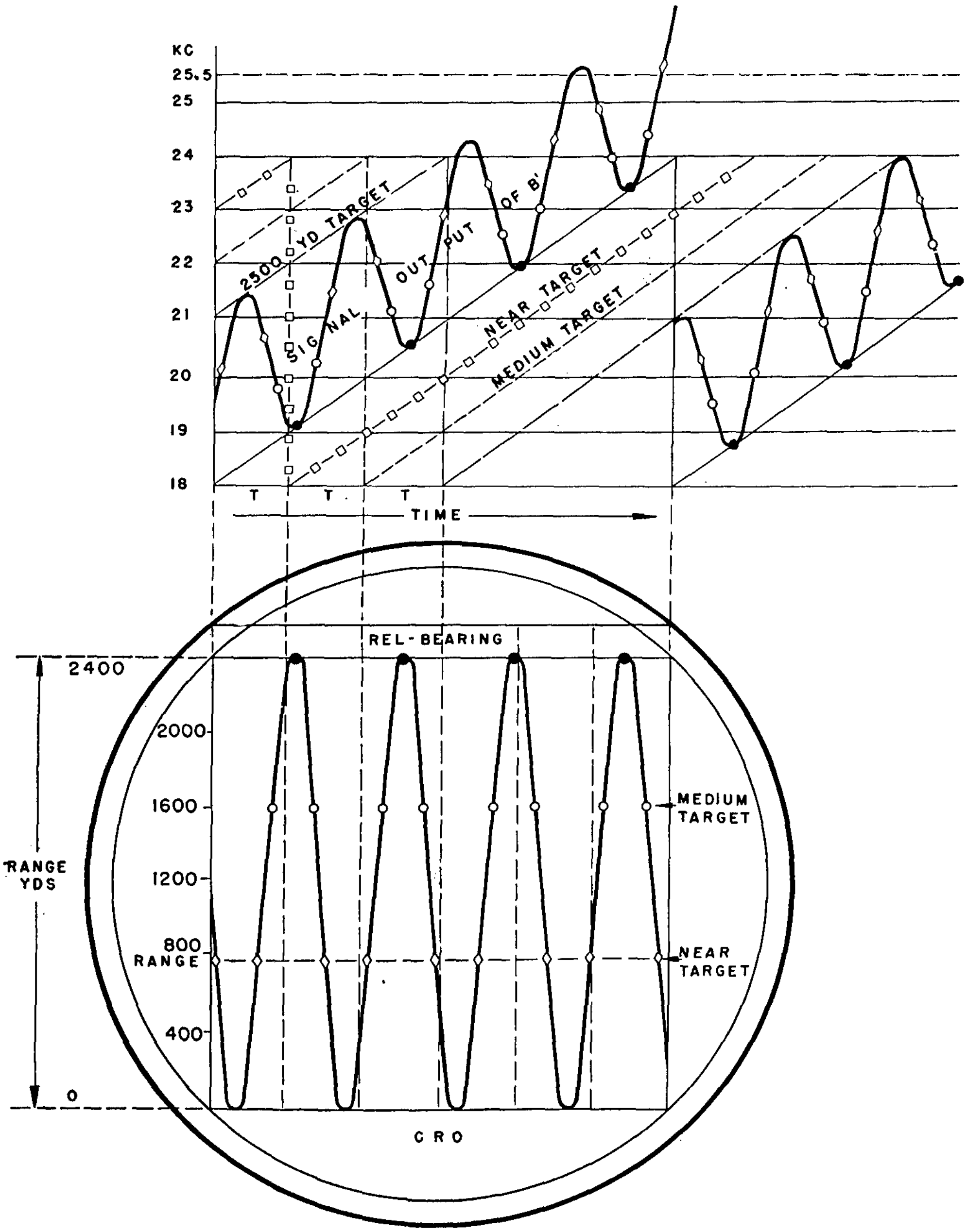


FIGURE 10. Pribar range indication functional diagram.

a 3-kc difference frequency once each cycle per second (20 times per sec) when heterodyned with the 2,400-yd echo. Hence, a pulse of energy is passed by the 3-kc filter once each cycle per

However, by reference to the upper half of Figure 10, it is also obvious that an echo returned from any range less than 2,400 yd produces when heterodyned with the special injec-

tion, a 3-kc difference frequency *twice* during each cycle per second of this special injection. The appearance of these indications on the CRO is diagramed in the lower half of Figure 10.

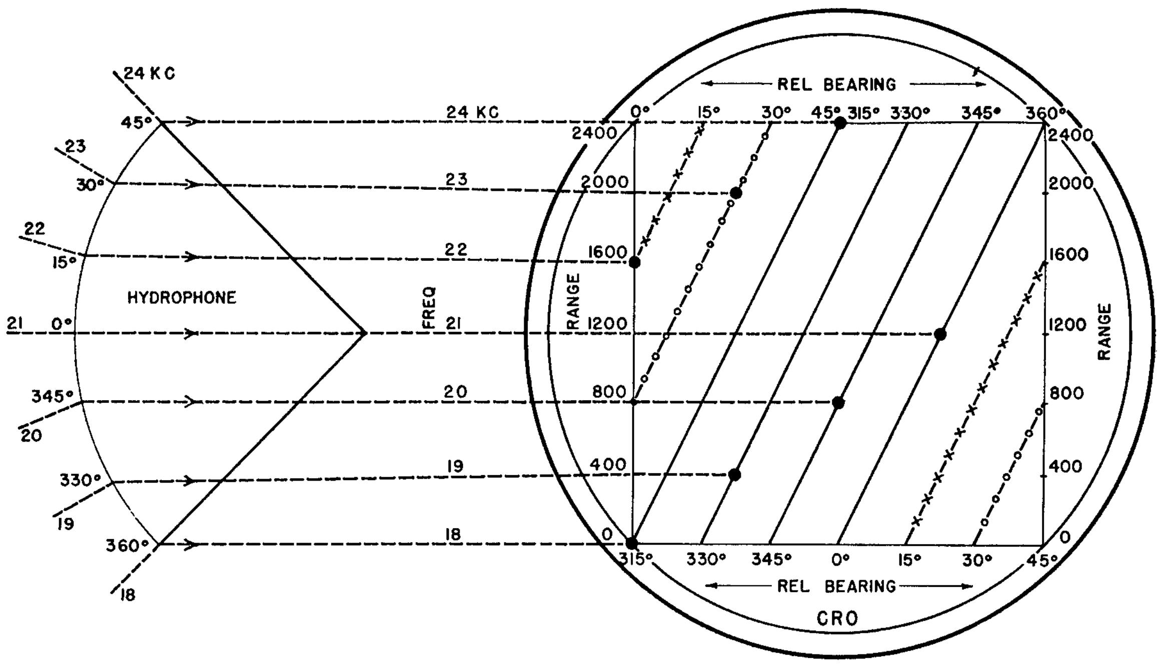


FIGURE 11. Pribar bearing indication functional diagram.

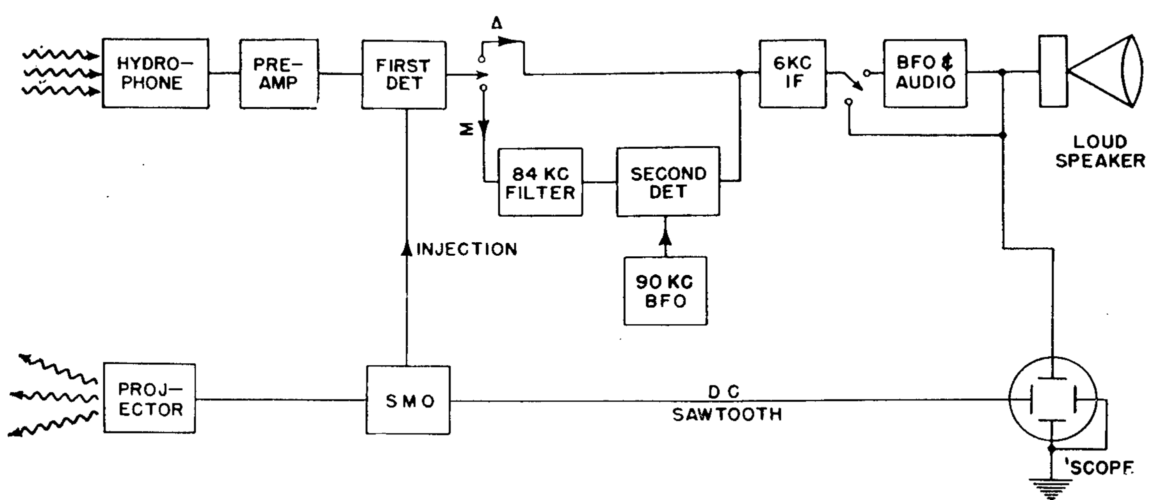


FIGURE 12. Sigma Cobar system block diagram.

Echoes from ranges above 2,400 yd could produce range ambiguities, but at the time of the Pribar investigation the system was not capable of recording echoes from ranges greater than 2,400 yd. If it had been, the problem could have been solved by focusing the system (by slowing the sawtooth repetition rate) on the maximum range of which the system was cognizant.

The vertical plates (V in Figure 9) of the CRO are driven by a portion of the output of the 20-c modulator, while a portion of the sawtooth voltage from A drives the horizontal

plates *H*. Thus, horizontal deflection on the CRO, indicative of bearing, is controlled by the transmitted signal.

Ideally, the Bell Telephone Laboratories' supersonic prism would scan bearing so that 21 kc would be indicative of a bearing normal to the crystal array 18 kc of 45 degrees to the left and 24 kc of 45 degrees to the right. For

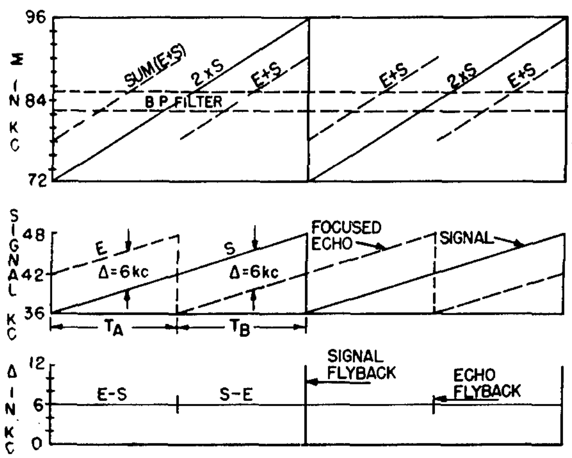


FIGURE 13. Sigma Cobar transmitted signal and echo.

example, if the prism were mounted normal to zero relative bearing of a vessel, 18 kc would be received exclusively from 315 degrees relative, 21 kc from 000 degrees, and 24 kc from 045 degrees. For targets at zero range (Figure 11) the base line of the scope would then be calibrated from 315 to 045 degrees. A target at *zero range* and at 315 degrees relative would appear as a spot at the lower left-hand corner of the picture. However, if this target were to move out in range to 2,400 yd along the same line of bearing, the echo at 18 kc would not be received until the spot had moved horizontally (as controlled by the output of *A*, Figure 9) to the center of the scope. At 2,400 yd, bearing 315 degrees relative, the spot would appear at the top center of the picture. Lines of constant bearing on the scope face are therefore *tilted* in the manner illustrated in Figure 11. This tilting distortion of the bearing indication in Pribar systems arose from the fact that horizontal deflection on the CRO was controlled by the sawtooth of the transmitted signal. A modification in which horizontal deflection on the CRO would be controlled by the sawtooth of the echo would have eliminated the distortion but before such a modification could be incorporated in the equipment, a demand arose for a production prototype of a standard Cobar system and further work on Pribar was held in abeyance.

Sigma Cobar. The Sigma modification of Cobar operation utilized *sum* frequencies for the determination of range rather than the difference frequencies utilized by Delta Cobar. In any detector in which two frequencies are heterodyned together, there is, in addition to the difference frequency arising from the two basic frequencies, a sum frequency whose value is equal to the total of the two basic frequencies. In an FM system operating on the 36- to 48-kc band with average frequency at 42 kc the sum frequencies fluctuate from 72 to 96 kc with an average frequency of 84 kc.

Passing the output of the first detector through an 84-kc sharp band-pass filter (see Figure 12) produced a Cobar sensitive to targets at any range but which did not have the

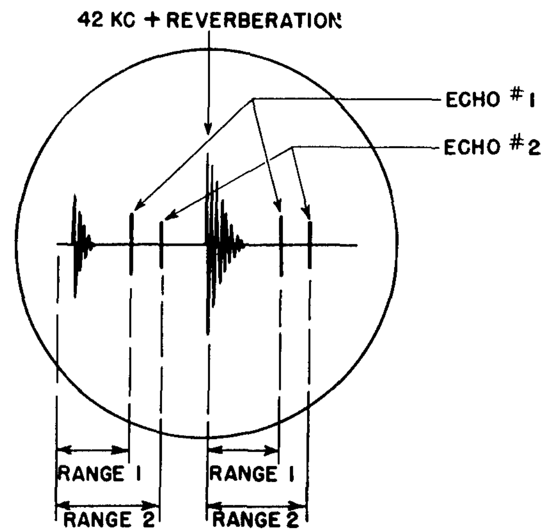


FIGURE 14. Sigma Cobar diagram of CRO indication.

focusing properties inherent in Delta Cobar which utilized difference frequencies only.

In Figure 13 are plotted the transmitted sawtooth signal and a returning echo together with their sum frequencies. During the sawtooth cycle the sum frequency fluctuates through

the band from 72 to 96 kc and crosses the 84-kc filter twice per sawtooth cycle. The sum frequency crosses the 84-kc filter twice per sawtooth cycle because the sum starts at the low end of its own frequency band both at the transmitted signal flyback and again at echo flyback. Thus, when the output of the first detector is fed through an 84-kc band-pass filter to an amplifier, the amplifier passes a pulse of energy twice per sawtooth cycle. These pulses take the form of a rising chirp of sound similar to the pings from a pinging system.

In scanning a sector in which several targets are present, Sigma Cobar sends a chirp through the filter twice per sawtooth cycle for each target present in the field. See Figure 14. Thus, with Sigma Cobar every target within audible distance sends chirps through the receiver and consequently all targets within the ultimate range of the system are presented in rapid sequence. Sigma Cobar operation offers automatic scanning in range in contrast to Delta Cobar in which range was scanned manually and the system was cognizant of only one range at a time.

Figure 14 diagrams the appearance of echoes on the CRO of the Sigma Cobar. The field shows two extraneous disturbances. One at the left is caused by signal flyback, and the one in the center of the field is caused by echo flyback. Both of these are enhanced by local reverberation. All targets within range in the line of sight show up as pairs of pips, one on either side of the center line of the CRO. The distance by which these pips are displaced from the left and from the center of the linear trace on the CRO (linear trace being furnished by the sawtooth generator) is a function of both their range and the period of the sawtooth generator. They are always delayed by a time that is identified with the range to the target from which a particular echo is received.

The FM system designated as Cobar Mark III was so arranged as to utilize both the sum frequencies and the difference frequencies present in its first detector. With this modification Cobar Mark III was capable of scanning automatically in range (using the sum frequency) and achieving great accuracy of range determination (using the difference frequencies).

The disadvantage of the Sigma Cobar method of operation lay in its lack of sensitivity. This arose from the fact that the extraneous disturbances occasioned by flyback occupied a relatively large portion of the CRO screen. In order to confine the targets to the remaining portion of the screen it was necessary to have the 84-kc filter very narrow. The Sigma Cobar system swept across this narrow filter so rapidly that only major targets had sufficient echo intensity to show as a trace on the screen through this narrow filter. Hence, any but very large and very solid targets were missed in the automatic scanning operation possible with Sigma Cobar.

Psi—Utilizing Sawtooth Flyback as a Ping. The Psi modification of Delta Cobar operation which proposed the utilization of the sawtooth flyback as a ping for rapid range scanning was proposed for incorporation into the FM system known as Cobar Mark III but was never actually built into the equipment because the multiple filter examination of the output of the first detector had just become available in the Fampas systems and attention was thereby diverted from single filter techniques of determining range. The proposed Psi modification of Delta Cobar operation is reported here not only because of its own significance but also because it is, at this writing, being investigated as a possible answer to the problem of doppler correction in all FM systems.

Assuming an upswept (positive) sawtooth (as existed in Cobar Mark III) the flyback brings the frequency of the transmitted signal back to 36 kc at the lower end of the operating band. A 30-kc fixed oscillator is used to provide a second source of injection into the first detector which is independent of the injection arising from the transmitted sawtooth signal. The 36-kc frequency occurring at the end of the flyback is heterodyned with the output of the 30-kc fixed oscillator, and the 6-kc difference frequency is passed by the 6-kc band-pass filter already present in the Delta Cobar receiver. For a negative sawtooth in which flyback returns the frequency to 48 kc the same procedure is possible by using a 54-kc fixed oscillator as the source of independent injection.

By means of this 30-kc fixed injection the

system is made cognizant of the 36-kc portion of the sawtooth signal as though it were a ping emitted at a fixed, 36-kc frequency, and without interfering with the FM operation of the system based on the sawtooth modulation of the signal. At the moment of flyback this ping with its associated reverberations is audible on the loudspeaker and appears on the CRO as a pip along the horizontal trace line. Following the pip of the flyback ping will be a series of pips (assuming several targets) in which each succeeding pip represents a target at increasing range. The succeeding pips occur as the echo-

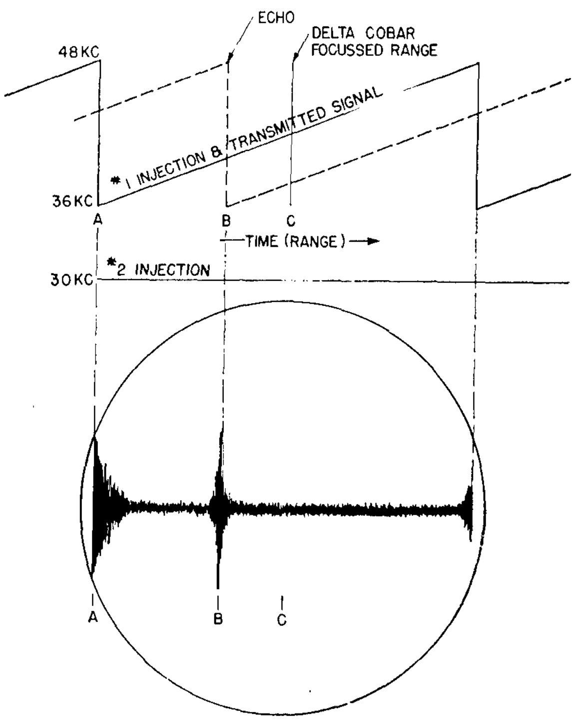


FIGURE 15. Psi diagram of CRO indication.

return from an individual target flies back to 36 kc and thus establishes a 6-kc difference frequency with the relation to the output of the 30-kc fixed oscillator. This 6-kc difference frequency is accepted by the 6-kc band-pass filter in the receiver. The displacement of target pips along the horizontal line of the CRO is a time displacement directly proportional to the range to the target from which the echo is being returned.

The operator may select any desired target as represented by a pip on the CRO and by adjusting the Delta Cobar range-control dial may move this selected pip to the center of the screen. As the desired pip approaches the center of the screen the two tones arising from the Delta Cobar function become audible in the loudspeaker and approach each other in frequency. When the two tones become identical in frequency it is evident that the system is focused accurately on the desired target. The accurate range to the target may then be read from the range dial. Once the desired target is brought to Delta Cobar focus it may be followed with great reliability while the Psi feature of the equipment continues to investigate all ranges within the heading of the hydrophone from zero to twice the Delta Cobar focused range. It will be remembered that the Delta Cobar system focuses on the given target by adjusting the sawtooth period so that the returning echo lags the transmitted signal by exactly one-half a sawtooth cycle. The Psi feature of the equipment is responsive to targets at ranges involving round-trip transmission time up to the full extent of the sawtooth cycle and, hence, twice as great as the range at which Delta Cobar is focused.

Figure 15 is a diagrammatic illustration of the appearance of the CRO of the Delta Cobar incorporating the Psi feature. In the diagram a Psi indication *b* may be moved by adjustment of the Delta Cobar range control toward the center of the CRO screen at *c* with the results described in the last paragraph.

While the single-filter examination of the output of the first detector in the development of range information together with the various modifications described offers possibilities for the development of unique underwater echo-ranging techniques, other methods involving the use of multiple filters and made possible by the development of a suitable electronic switch seemed to be more versatile. With Fampas and subsequent FM systems, attention was accordingly concentrated on the multiple-filter techniques of developing range information.

Multiple Filter Examination of Output of First Detector

In January 1943, a proposal was made that the FM system scan range automatically by

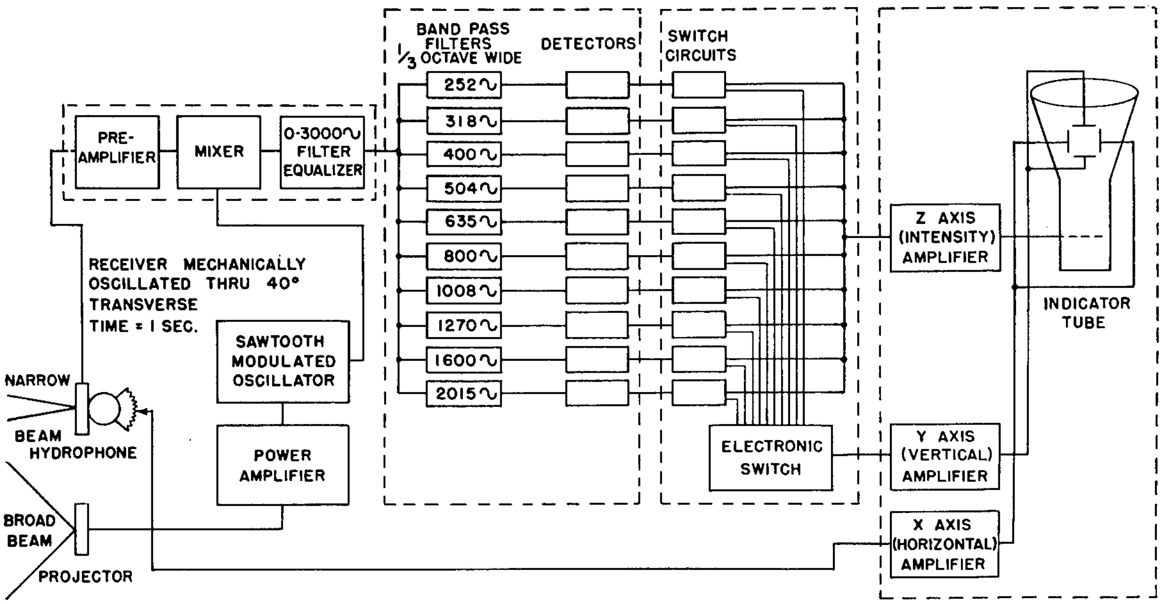


FIGURE 16. Fampas system block diagram.

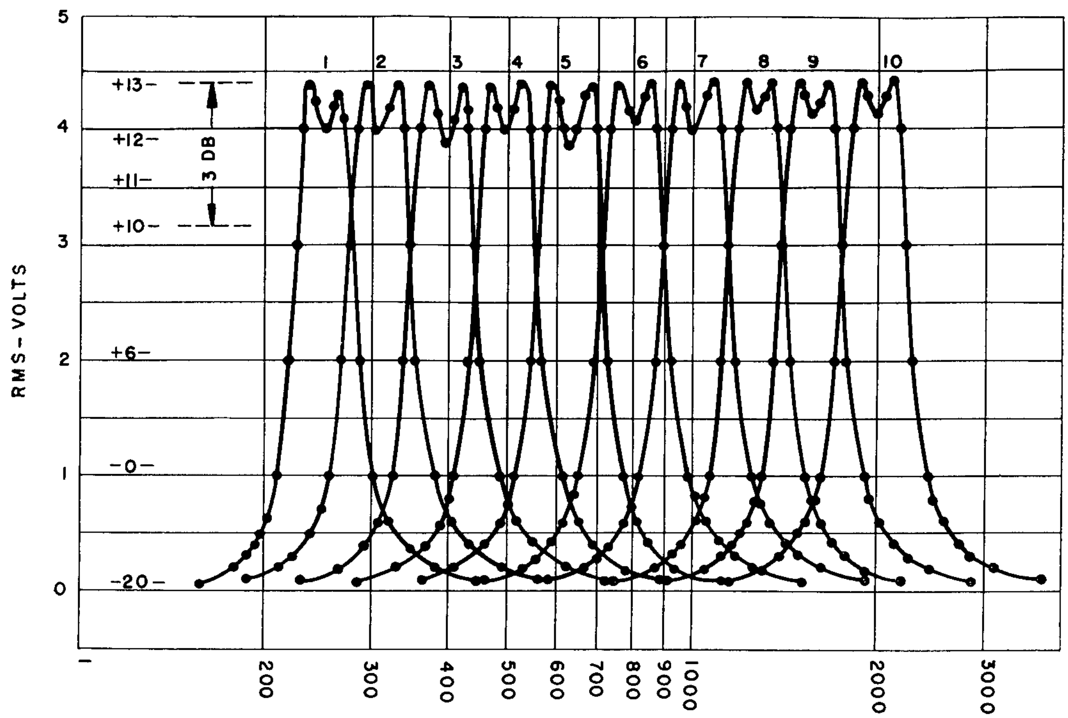


FIGURE 17. Fampas filter channel response curves.

analyzing the output of the system's first detector with multiple filters instead of with the single-filter methods just described.[19]

Single-filter examination of output of the first detector required that the system remain focused on one range long enough to secure a statistical averaging of any signal returning from that one range. On the other hand, to approach the ideal in range-scanning speed the system should remain focused on one range only for the minimum length of time necessary to resolve the signal information available from that range. Attempts to compromise these two apparently conflicting requirements would penalize either the scanning speed or the signal averaging property of the system unless some means of integrating (storing) the signal energy received from various ranges is provided. With provision made for such storage of range information, scanning may be done with extreme rapidity and without sacrificing the signal-averaging feature inherent in FM operation. The Fampas proposal outlined a means of accomplishing this.

In an FM system where the frequency of the transmitted signal varies in a sawtooth pattern it is obvious that: (1) the time-frequency relationship of the sawtooth modulation has the effect of converting range information into a frequency spectrum; (2) the continuous nature of the transmission makes range information continuously available in the output of the first detector; (3) the storage of signal energy received from targets at varying ranges may be accomplished in frequency-selective channels corresponding in frequency limits to the ranges in which we are interested; (4) the output of these individual channels may be rectified and applied to individual *RC* networks of such time constants that the voltage decay occurring between scanning periods is negligible; and (5) the *RC* networks may be scanned sequentially and rapidly with some sort of switch while the filter channels are continuously averaging the signal presented to them.

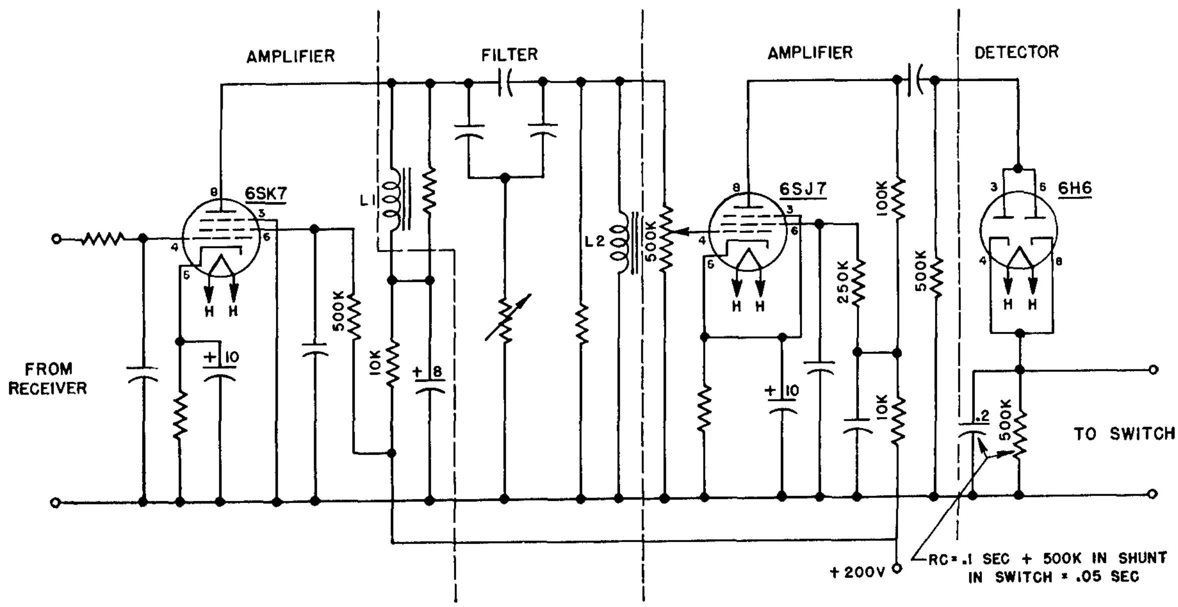


FIGURE 18. Fampas schematic diagram of analyzer channel.

Figure 16 is a block diagram of the Fampas system proposed to accomplish the functions described above. The receiver pass band following the first detector was originally designed to accommodate frequencies from something under 100 up to 3,000 c with a sharp cutoff at the 3-kc end to eliminate range ambiguities (see Section 2.2.6). After suitable amplification, the major portion (225 to 2,250 c) of this band was divided into 10 logarithmic components by a set of 10 filters. (See Figure 17.)

Each filter covered a logarithmic fraction of the 225- to 2,250-c band, and the frequencies accommodated by each filter represented successive logarithmic fractions of the maximum range for which the system was set. Logarithmic distribution of filter widths gave rise to some distortion of range indication, because under this arrangement range resolution is a percentage function of range.

Figure 18 is a schematic diagram of a typical analyzer channel composed of filter and associated *RC* network as used in Fampas Mark I. Each of these channels was so tuned as to overlap adjacent channels at the 3-db downpoints (Figure 17). The energy passing through each filter was amplified, rectified, and stored in an *RC* circuit having a time constant of 0.05 sec.

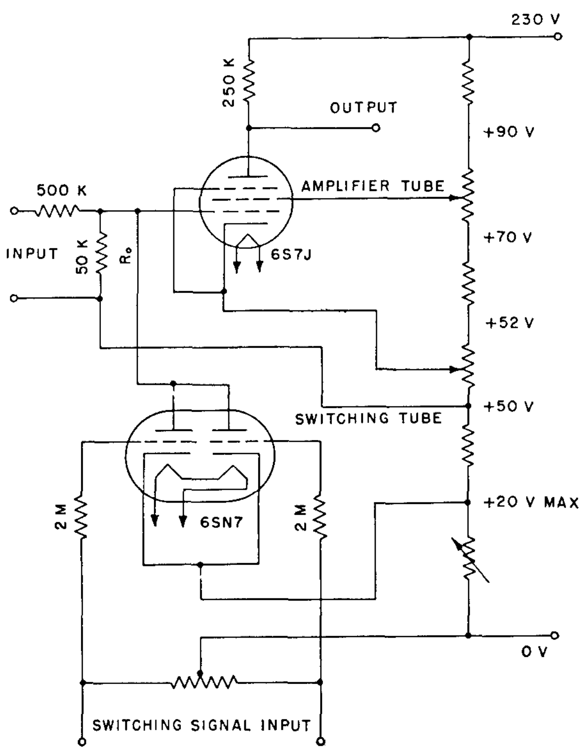


FIGURE 19. Fampas schematic diagram of multichannel electronic switch.

Proper synchronization of the application of the energy in these 10 *RC* circuits was achieved with a UCDWR-developed phase-shifting, electronic switch[2] as diagramed in Figure 19.

In this basic switch element when no switching signal is applied both sections of the switching tube are biased beyond cutoff. Under this condition the switching tube has no effect on the amplifier tube circuit which then behaves like a normal amplifier. When a sinusoidal switching signal is applied for a portion of the cycle in the neighborhood of zero voltage both sections of the switching tube are cut off so that the amplifier operates normally. For ordinary switching signals there is a considerable portion of the sinusoidal cycle where one of the switching tube sections becomes conducting; one on *positive* swings of the signal, the other on *negative* swings. When this occurs, the plate current of the switching tube, flowing through the resistor into the switching plates in the grid of the amplifier tube, causes the bias on the amplifier tube to increase beyond the cutoff value. This opens up the switch element. Since the conducting period of the individual switch element is controlled by the phase of a sinusoidal switching signal, a phase-shifting network is all that is needed to obtain the switching sequence. Such a phase-shifting network was designed which operated from the 60-c line as a source of sinusoidal voltage. Because the sweep along the radius of the CRO was controlled by the same 60-c line voltage, this switching arrangement satisfied the basic requirements for synchronization. Subsequent development work resulted in simplifying the circuits of this multichannel switch. A complete description of it in the form in which it appears in QLA-1 will be found in Chapter 5.

The 10-channel analyzer just described performed the function for which it was intended but did not provide adequate range resolution.

A second analyzer utilizing 20 channels distributed between 225 and 2,250 c (each channel having a bandwidth of one-sixth octave) was constructed for Fampas Mark II. This second analyzer covered the same sound spectrum as the first but with 20 channels instead of 10. As before, each channel was tuned to overlap adjacent channels at the 3-db down points.

The use of a greater number of narrower filters to cover the same spectrum resulted in the expected increase in range resolution. But it appeared that further range resolution could be achieved by different distribution of the filters in the spectrum. Observation of the fre-

quencies accommodated by the analyzer, ranging from 225 to 2,250 c, indicates that the outside range is approximately 10 times the minimum range of which the system is cognizant. Although it is highly desirable to have as large a ratio in this respect as possible, such an arrangement presents two difficulties: (1) because the filter arrangement is logarithmic the longest range of which the system is cognizant is accommodated by the widest filter, thus giving a poor signal-to-noise ratio on weak targets (those at great range) just where a high signal-to-noise ratio is important; and (2) because range accuracy is a percentage function of range, the absolute range accuracy at long ranges is sacrificed. In an effort to overcome these difficulties, subsequent filters were constructed so that the distribution of filter widths throughout the spectrum was on a linear basis. Experimentally it was determined that a 75-c channel width gave sufficient range resolution and accordingly the spectrum now covered by the 20-channel analyzer extended from 500 to 2,000 c thus sacrificing the 10-to-1 ratio between maximum and minimum ranges in favor of greater range resolution.

The linear distribution of filters not only improved signal-to-noise ratio at long ranges, but restriction of the receiver pass band to 2,000 cycles per second reduced the possibility of range ambiguity in that the shortest possible range which could now give an ambiguous indication was 5 times as great as the maximum range for which the system was set. This factor of five was an improvement over the factor of three which had been valid for a system employing a 3-kc pass band. The 500- to 2,000-c spectrum, the 75-c bandwidth, and the linear arrangement of filters throughout the spectrum are used in QLA-1 equipment.

In addition to the linear arrangement of the 20 channels the analyzer incorporated two other new features: (1) automatic reverberation control of gain which established a threshold level, making the system more or less insensitive to reverberation disturbance; and (2) discrimination against extremely short pulse lengths in which the detector itself was changed from the diode type to a linear type to accommodate these two new features which resulted in increasing the visual equivalent of the signal-to-noise ratio of the CRO presentation. By suitable selection of *RC* time constants in the detector circuit and the storage circuit following each analyzer channel, the system was rendered relatively insensitive to extremely long pulses arising from reverberation as well as to extremely short pulses. Thus the system was effectively sensitive only to those pulses measured in tenths of seconds which arose from the scanning action of the hydrophone in crossing the bearing of a wanted target.

To make reverberation controlled threshold [(gain) (see Figure 20)] possible, an *RC* network in the grid return of the detector was coupled to its cathode in such a manner that the input signal controlled the bias. For signals of long duration the voltage developed across the cathode resistor had sufficient time to charge the *RC* network condenser, thus increasing the bias and therefore decreasing the effect of the signal. This allowed the use of higher receiver gain without having reverberation light the screen and resulted in a high sensitivity to desired signals.

The discrimination against pulses of extremely short lengths (noise) is achieved by an *RC* storage circuit of such a time constant that an extremely short pulse operating through a resistor (.10 megohms, Figure 20) is not able to charge the condenser of the *RC* network with sufficient energy to be recorded on the CRO. This resistor proved to be a voltage divider; in subsequent circuits the plate load resistance (.05 megohms) was connected directly to the plate to obviate this difficulty. Variations in the time constant of this *RC* circuit can be manipulated in such a way as to provide a system sensitive to any desired pulse length (the optimum time required by the hydrophone beam to scan across a target).

At this point, the analyzer development had reached substantially the stage at which it exists today in QLA-1. For complete description of the analyzer in present equipment (as of the date of this report) see Chapter 5.

The Light Valve. During tests with the Fampas Mark II system, some consideration was given to the use of a tuned reed acoustic spectrometer for its greater resolving power. In

theory such a device should replace the filter channels, amplifier, switching arrangement, and CRO of the Fampas system.

Accordingly, a tuned reed acoustic spectrometer was ordered from the Bell Telephone Laboratories.[20]

Results with this unit were sufficiently promising to result in the placing of an order for a similar unit with the Electrical Research Products Division of Western Electric Co. to be adapted to the specific requirements of FM systems. Concurrently with the placing of this order, UCDWR started to build a similar unit. (See Section 7.2.)

By the time that the ERPD unit was delivered to UCDWR in June 1944 the FM system was considered a prosubmarine device and space was at a premium. The multichannel analyzer was a more compact unit than the light valve and consequently the analyzer took precedence over the valve in the construction of subsequent systems.

The great resolving power of the acoustic spectrometer over a wide range of frequencies seems to merit further consideration of its use in an FM system application.

3.3.3 Receiver

The FM receiving system consists of a hydrophone, a coupling network, a first detector or mixer in which the echo is heterodyned with a portion of the transmitted signal, a slope amplifier, and an output stage. The portion of the transmitted signal which is fed into the first detector is conveniently referred to as injection to distinguish it from the voltage fed to the driver amplifier for projection into the water. The output of the first detector then enters a bandpass amplifier which brings it up to a level appropriate for either aural or visual examination.

One of the basic problems of FM systems receivers arises from the fact that leakage from the projected signal is picked up (through a short water path) by the hydrophone of the system and unless dampened in some way interferes with echo indication. A second important consideration in a receiver suitable for use in an FM system is that it be sensitive enough to detect signals of the order of 1 to 5 μv.

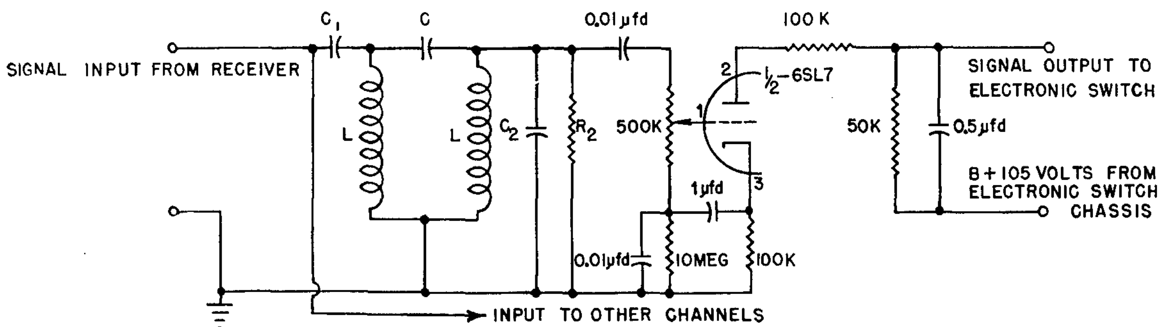


FIGURE 20. Pulse discrimination circuit schematic diagram.

Starting with the Point Loma receiver which was being developed by UCDWR during the time that Brush Development Co. was constructing the first echoscope system, and extending through all the Cobar systems, this extreme sensitivity was achieved by the following process: (1) preamplification of the received echo prior to its entry into the first detector, (2) amplification of the 6-kc output of the first detector, and (3) a third amplification of the signal after it had been heterodyned down to the audio level at 800 c.

In these same systems the disturbing effect of leakage was overcome by the use of a balanced-modulator type of first detector employing a copper oxide varistor. It was found that this type of detector when well balanced against the frequencies of the projected signal made it possible to discriminate against leakage (crosstalk) between the projector and hydrophone.

The two previously reported modifications of the Cobar systems, Pribar and Sigma Cobar,

saw a modification of this receiver as required by the peculiarities of these two systems. In Pribar the receiver was modified to accommodate a special injection frequency, and in Sigma Cobar was modified to operate on the sum of the frequencies as well as the difference frequency which was utilized in a standard Cobar procedure.

The Cobar systems utilized a 6-kc band-pass amplifier. The sharpness of the 6-kc band-pass filter determined the signal-to-noise ratio and the sharpness of focus of the system. Selectivity of the i-f amplifier incorporating this filter was sufficient to reject any echo which did not give a beat frequency of 6,000 ± 300 c with the transmitted signal. Multichannel analysis of the output of the first detector, on the other hand, called for simultaneous handling of echoes from a number of different ranges. To meet this demand the pass band of the receiver amplifier was broadened (from 6 kc ± 300 c) to accommodate frequencies from something less than 100 c to a top limit of 3,000 c.

Since all amplification must necessarily now occur in the audio band, very careful redesign of the receiver was necessary to eliminate acoustic feedback, microphonics, and other types of internal set noise.

In the Fampas systems the development of more efficient projectors resulted in a leakage injection value of 50 to 70 db above the strongest echo being received. Under these conditions preamplification of the 36- to 48-kc signal tended to overload the first detector and therefore preamplification was eliminated from Fampas and subsequent systems.

Early in the course of tests with Fampas it was found that a receiver with a flat frequency response was not desirable. The Fampas practice of accepting echoes simultaneously from a number of ranges (these echoes decreased in strength in geometric ratio with increasing range, assuming targets of similar echo strength) made slope amplification necessary to give targets of equal echo strength a representation of approximately equal intensity on the screen of the CRO. Since in FM systems frequency increases as a function of range, slope amplification was achieved with an amplifier which applied gain of increasing magnitude as the frequency increased. Frequency-dependent amplification at the rate of 12 db per octave (see Figure 21) has theoretical justification corresponding exactly to the inverse fourth power law of divergence. This arrangement also met the requirements of a situation in which the variation of echo strength arose from the fact that the echo-ranging ship was closing (or opening range) on a target.

A manual gain control is provided to accommodate the system to varying echo-ranging conditions (varying classes of targets, varying water conditions, etc.), and this manual control does not materially affect the frequency-dependent characteristics of the slope amplification. This means that the slope amplification of 12 db per octave works off the manual gain control setting as a reference level so that any place within the range of the manual control the frequency-dependent slope adds 12 db of amplification for each octave increase in the frequency.

The understanding of receiver problems gained from the development work with all the systems covered in this report indicates that it is necessary to have 145 to 150 db of amplification (while maintaining a signal-to-noise ratio of at least 6 db) in the receiver in order to obtain maximum ranges on the 3,000-yd scale of the system. The characteristics of a receiver making this possible are covered in Section 2.2.

3.3.4 Aural and Visual Presentation of Information

During the early stages of the FM systems program, the emphasis on the presentation of the information was on an aural presentation through a common loudspeaker. The reason for this lay partly in the fact that there were so many difficulties of first order importance to overcome in learning to use an FM signal in underwater echo ranging that little attention was paid to the actual problem of presenting the information in a concise and usable form.

With the advent of the multichannel analyzer (Fampas) which made it possible to portray echoes simultaneously from a number of differ-

ent ranges in the form of a PPI plot, the emphasis shifted to visual presentation and tones from the loudspeaker became an auxiliary or supporting indication.

SPEAKER

In early systems the output of the receiver was heterodyned to 800 c and the characteristics of the speaker were relatively unimportant. These early systems utilized difference-frequency "images," spread on either side of the was at all weak. This difficulty arose from the fact that as the two tones arising from the images approached each other in frequency, the speaker was not of a quality which made small differences in tones easily recognizable.

This realization led to the employment early in the Cobar development and for all subsequent systems of a relatively high-fidelity speaker. Until the development of the Fampas system the speaker continued to be the main instrument of range determination with the trace on

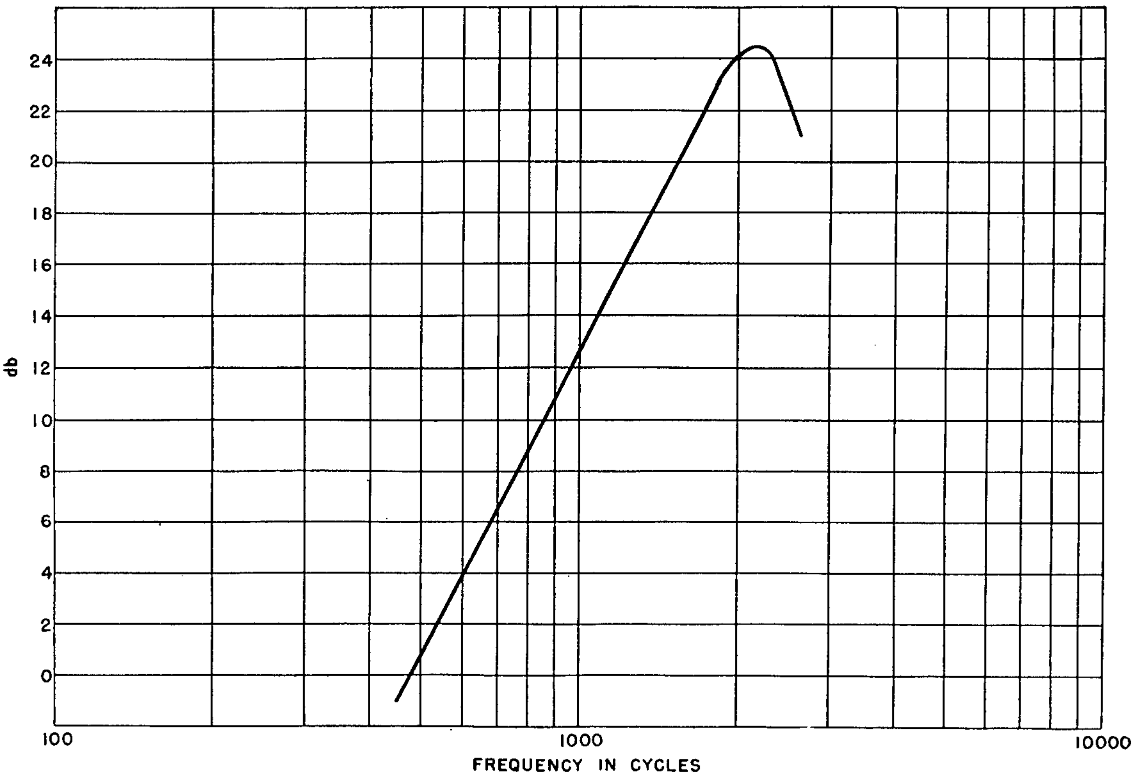


FIGURE 21. Slope amplification in receiver, frequency response curve.

sawtooth signal, as an indication of range in which it was necessary to compare the tones produced by these two frequencies. Identical tones arising from these two images were fixed by the parameters of the system at 6 kc each. It was possible, however, to have any combination of frequencies within the comprehension of the band-pass filter which would total 12 kc. It was soon discovered that even when suitable echoes could be obtained it was very difficult to differentiate properly between on-target and off-target adjustment when the target response the CRO serving as an auxiliary indication and primarily useful only for determination of echo intensity.

The FM system (QLA-1) as of the date of this report utilizes a 6-in. permanent magnet speaker of medium fidelity with essentially flat response from 70 c to 7,000 c.

In QLA-1 the problem is not one of matching difference frequency images, but the speaker serves a valuable purpose in assisting in the identification of the character of targets. As the soundhead scans the field the CRO screen

may show numerous target indications which may vary in intensity, size of the trace, etc. Out of this mass of target information (on the CRO) the clear, singing tone emitted by the loudspeaker quickly identifies a solid-target contact. The function of the loudspeaker is particularly valuable in differentiating the echo of a small object from reverberation and other extraneous noises.

Cathode-Ray Oscilloscope [CRO]

Because early emphasis was on the aural presentation of information rather than visual the first CRO was a 5-in. Du Mont test oscilloscope.

One of the earliest attempts to present range and bearing information visually occurred in the Cobar modification known as Pribar and the demands of the Pribar system made necessary a better CRO. Accordingly a 9-in. CRO with long persistence screen was used, employing intensity modulation. An attempt was made to use a raster similar to that in television practice on the screen of the CRO. Horizontal deflection indicated bearing and vertical deflection indicated range. The raster itself was kept below a threshold incorporated in the systems so that it did not interfere with the indication; a target would be indicated by a bright spot at the appropriate vertical elevation on the raster and in a horizontal deflection indicating bearing.

The next development in which the CRO appeared as an important indicating device came in the use of a 7-in. scope as a range indicator with the Sigma Cobar systems which represented an early attempt to scan range automatically. With Fampas systems the CRO really came into its own as a means of indication.

The first Fampas system made its presentation in the form of a plot using Cartesian coordinates. Range was indicated by vertical deflection from a base line, and bearing was indicated by horizontal deflection from the center of the scope. Each of the system's ten channels had an appropriate vertical segment of the CRO screen for its presentation. The output of these channels was kept below the visual threshold in the absence of a target, but the presence of a target excited a filter (appropriate to its range) and resulted in the intensity rising above the visual threshold so that it appeared as a spot on the screen at a distance from the base line proportionate to the range from echo-ranging vessel to the target.

The Cartesian coordinate type of plot was not as readily interpretable as a PPI presentation of the same information. Accordingly, attention was turned to the development of a PPI presentation of the same information on the CRO in which the position of the echo-ranging ship was identified with the center of the PPI plot. Range was indicated as radial distance from this center, and bearing information was presented relative to the heading of the echo-ranging vessel as identified with the top of the CRO. To make this PPI presentation possible, a radial sweep CRO was designed in which a sine potentiometer mounted on the hydrophone column related the bearing indication on the scope to the training of the hydrophone. With the radial sweep, the output of the filters corresponding to various ranges were represented as concentric rings extending out from the center of the scope with the minimum range closest to the center and the maximum range at the outer limits of the scope.

Early experimental work with the radial sweep CRO brought to light two serious problems:

1. The radial sweep was not a true circular trace; in essence the radial deflection was a function of the vector sum of all four deflection tubes. To produce a true circle under these conditions it would be required that all four tubes used in the system have identical characteristics; and this was not practicable with production-type components. The answer to this problem was found by redesigning the circuit to incorporate degenerative characteristics which canceled the unbalance of the four deflection tubes.

2. The second serious problem encountered was the fact that the original amplifier[18] used with the radial sweep CRO had a limited dynamic range which resulted in a low-recognition differential. A new intensity amplifier (tube V-811, Figure 48, Chapter 5) was designed with a higher dynamic range characteristic which made it possible to increase the dif-

ference between on-target and off-target indications and thereby produce the visual equivalent of a high signal-to-noise ratio.

With these two problems solved the CRO maintained its basic design throughout all subsequent systems.

With the adaptation of equipment for prosubmarine use it became necessary to concentrate all the controls of the system in the same panel with the indicator and make them as compact as possible. Chapter 5, covering QLA-1 equipment, shows the stage to which this development had progressed at the time of this report.

Range and Bearing Reticle. Relative bearing is indicated on a bearing ring surrounding the face of the CRO in which zero relative bearing with respect to the heading of the echo-ranging vessel is at the top of the scope. The range and bearing reticle is a Lucite disk superimposed on the face of the scope and carrying three radial lines indicative of the three maximum ranges corresponding to the three maximum range settings possible with the equipment. In echo ranging on a specific target the reticle is rotated until the appropriate range line bisects the target indication on the screen of the CRO. With the reticle in this position it is possible to read the range of the target from the calibrations along the appropriate range line of the reticle. The end of such range line points to the proper bearing indication on the bearing ring surrounding the scope.

The type of reticle just described was first used with FM Sonar Model 1 No. 1, and with the same system some special types of reticle were developed which attempted to compensate for doppler effect. With this minor deviation, the reticle remained essentially the same throughout the balance of the development to the QLA-1 system (Figure 3, Chapter 5).

Chapter 4

DEVELOPMENTAL SYSTEMS

THIS CHAPTER dealing with the developmental systems anteceding QLA sonar should prove valuable as reference material for those concerned with the echo-ranging problem.[a] The system cataloging will be divided into five major sections:

Cobar: COntinuous Bearing And Range
Pribar: PRIsm Bearing And Range
Subsight: SUBmarine SIGHT
} Antisubmarine Devices Only

Fampas: Frequency And Mechanically Plotted Area Scan

FM Sonar: Frequency-Modulated SOund Navigation And Ranging

The first echoscope later designated as Cobar Mark I, headed the series of frequency-modulated developmental systems. The new approach to efficient echo-ranging had as an ideal the production of a device capable of giving accurate bearing and range of a target as well as visual and aural definition of its character. First emphasis, however, was placed on aural monitoring of echo signals for antisubmarine operation.

4.1 COBAR SYSTEMS

An important correction must be made to Cobar measurements in order to make them comparable with pulsing methods. This correction arises from the fact that in the case of Cobar the radial thickness of the layer of water from which reverberation is received increases with the range setting. On the other hand, when a pulse is used the thickness is proportional to the pulse length. Cobar focuses on a particular layer of water at a given range but the *depth of focus,* and hence the depth of reverberating annulus, is directly proportional both to the width of the band-pass filter in the i-f chassis and inversely proportional to the rate at which the frequency is changing in the Cobar sawtooth cycle. In a sense one may say that Cobar functions as a pulsing device in which the pulse length is automatically increased proportionally with range.

[a] Microfilms of schematic diagrams for all systems and their major components are found in FM Sonar Systems Detailed Development References.[18]

Two distinct methods of measuring range were incorporated in the various Cobar modifications, the first by proportionality to difference frequency (Delta Cobar) between transmitted and received signals and the second by the sum frequency measurement (Sigma Cobar). Since the series of systems incorporated both Sigma and Delta types, often using both on a single mark unit, no further breakdown will be attempted.

The definitive characteristics of the Delta Cobar series are:

1. Cognizance of a single difference frequency at a time.
2. Scanning frequency, proportional to range, variable by manual adjustment of the sawtooth period in such a way that the difference frequency arising from transmitted signal and target echo at any range (within the comprehension of the system) could be brought within the single filter (e.g., 6 kc $\pm$ 200 c).
3. Determination of sawtooth period adjustment at which system is "on target" by aural comparison of "mirror image" difference frequency tones arising from the fact that parts of the echo sawtooth appear on both sides of the signal sawtooth, changing sides at moment of flyback. Equality of tone indicates correct adjustment balance.

The definitive characteristic of the Sigma Cobar series is: Range-scanning device (i.e., all targets within the range of detection are scanned consecutively throughout the sawtooth cycle). This property places Sigma Cobar in exactly the same category as the pinging devices. The following achievements were made possible by the Cobar systems:

1. Certain fundamental measurements, heretofore considered impracticable, were made, such as the relative response from a 6-ft triplane, a 10-ft sphere, a submarine (conning tower, body and wake separately), screw noises.

2. Cobar made possible for the first time the investigation of bodies of water remote from the hydrophone without the necessity of searching the area lying closer in the same sector. The time gained was used to obtain nearly continuous information from this particular point of interest remote from the hydrophone.

3. Many accessories theoretically thought to be practical were proved unsatisfactory by test. Among these were provision for frequency modulating (up to 1,500 c) the transmitted energy, 200-c audio oscillator, a detector doubler in the audio circuit, etc.

Eight experimental models of Cobar were constructed. The following sections tabulate the individual design modifications as the development proceeded.

4.1.1 Cobar Mark I

Visual Indication

The externally-connected 5-in. Du Mont *cathode-ray oscilloscope* [CRO] was fed from a diode rectifier in the audio output circuit. The internal sweep of the CRO was synchronized with the sawtooth.

Driver Amplifier

The output transformer secondary was tapped to provide impedance matching for loads between 100 and 2,500 ohms. A thermocouple, ammeter, vacuum-tube voltmeter, and ventilating fan were built in.

DATA SHEET—*Cobar Mark I*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	Brush Development Co.
Type	Superheterodyne
Gain	95 db
Output	1 watt
Intermediate frequency	6 kc
bandwidths	Broad, 400 c; Medium, 160 c; Sharp, 100 c } down 3 db
Audio output frequency	800 c
Sawtooth-modulated oscillator [SMO]	Brush
Type	Reactance modulated oscillator
Sawtooth slope	Up
Range scale	10 to 3,200 yd
Flyback blanking	None
Pinging provision	None
Listening provision	None
Doppler correction	None
Signal indication	Loudspeaker and 5-in. Du Mont* CRO
Driver amplifier	Two 813, push-pull
Output	200 watts @ 42 kc
Projector	One Brush C13
Hydrophone	Eight Brush C13's
Physical assembly	Two 48-in. relay rack cabinets
Location	Barge No. 2

* The 5-in. CRO was externally connected. A 1-in. CRO for alignment and indicating purposes was eliminated.

4.1.2 Cobar Mark II

Modifications

The Mark II Cobar consisted for the most part of the Mark I equipment, Figure 1, with the exception of the *sawtooth-modulated oscillator* [SMO] which was designed and constructed by the Hewlett-Packard Company.

Visual Indication

The receiver output was connected to the oscillograph vertical plates through a diode rectifier while the sawtooth was connected to the horizontal plates through a cathode follower. This provided a visual plot of echo signal amplitude versus the linear time base.

Sawtooth Modulated Oscillator

The oscillator, Model No. 426,[15] consisted of a sawtooth generator controlling the frequency of a positive-bias multivibrator. The repetition rate was adjustable from approximately 0.12 to 40 c and the output was coupled through a low-pass filter to a 1-watt output stage.

Flyback Blanking

Two conditions contributed to a disturbance during the SMO flyback period.

1. The transient nature and steep wave front were inherent in the flyback.

2. The flyback had a finite slope so the sys-

tem actually focused on targets at ranges of a few feet.

Consequently, a discriminator-actuated relay was added to the system to shunt the loudspeaker during the flyback transient and eliminate the majority of unwanted noise. This type of blanking while a considerable improvement did not eliminate the disturbance caused by reverberation immediately following flyback.

DATA SHEET—*Cobar Mark II*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	Brush Development Co.
Type	Superheterodyne
Gain	95 db
Output	1 watt
Intermediate frequency	6 kc
bandwidths	Broad, 400 c; Medium, 160 c; Sharp, 100 c (down 3 db)
Audio output frequency	800 c
Sawtooth-modulated oscillator [SMO]	Hewlett-Packard Model 426
Type	Voltage-sensitive oscillator
Sawtooth slope	Up
Range scale	100 to 3,000 yd 30 to 140 yd
Flyback blanking	None (originally)
Pinging provision	None
Listening provision	42 kc ± 500 c
Doppler correction	None
Signal indication	Loudspeaker and 5-in. Du Mont CRO*
Driver amplifier	Two 813, push-pull
Output	200 watts @ 42 kc
Projector	One W.U.†
Hydrophone	Eight Brush C13's
Physical assembly	Two 48-in. relay rack cabinets
Location	Barge No. 2

* The 5-in. CRO was externally connected.

† Type W.U. designation for projector manufactured at Wesleyan University, Middletown, Connecticut, replacing Brush C-13 in earlier tests.

4.1.3 Cobar Mark III

MODIFICATIONS

The Mark III Cobar consisted for the most part of the Mark II equipment with the exception of the SMO which was a laboratory-built modification of the Hewlett-Packard oscillator.

RECEIVER

During the course of the work with Mark III the first detector was changed to a 6SA7 tube

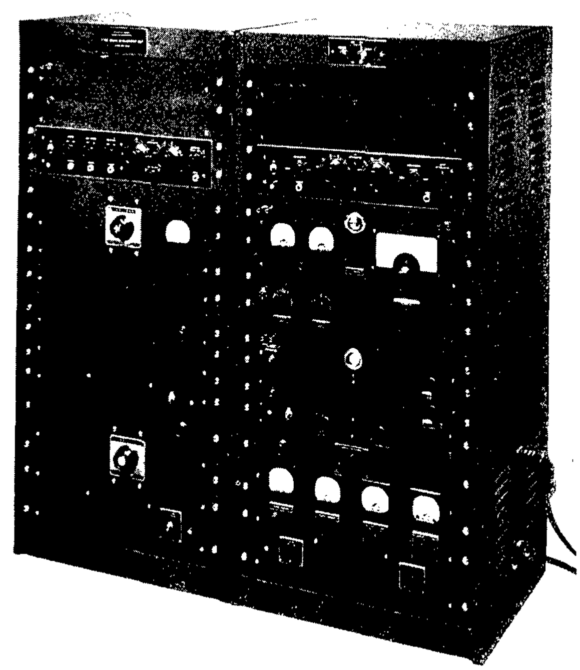


FIGURE 1. Cobar Marks I and II (UCDWR Barge No. 2 installation).

and later to a copper oxide ring modulator which has proved most satisfactory. The ring modulator produced a marked improvement in the separation of weak signals from reverberation.

The receiver was further modified to permit the characteristic range scanning operation of Sigma Cobar, i.e., measurement of sum rather than difference frequencies. Either Sigma or Delta operation could be selected by a switch.

FMO

Two frequency-modulated oscillators constructed at UCDWR were used with this sys-

tem. The first, known as the HE-3, was a copy of the Hewlett-Packard Model 426. The second, the RO-1, contained all the desirable features of Model 426 in addition to circuit modifications which improved linearity and stability. A selector switch allowing listening at three fixed frequencies, 36, 42, and 48 kc, was also included. The listening frequencies, 1,000 c wide, were displaced from the fixed frequency on the selector switch by ± 6 kc.

FLYBACK BLANKING

The discriminator type of blanking used with Mark II was discarded in favor of a new type independent of frequency. A second ring modulator used as a gating circuit in the output of the FMO was held open by a positive potential. Removing the potential closed the gate, dropping the output approximately 60 db. The pulsing network which removed the modulator potential was actuated by the start of the sawtooth flyback.

DATA SHEET—*Cobar Mark III*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	Brush Development Co. (modified)
Type	Superheterodyne
Gain	95 db
Output	1 watt
Intermediate frequency	6 kc
Audio output frequency	800 c
Sawtooth-modulated oscillator [SMO]	HE-3 and RO-1*
Type	Voltage-sensitive oscillator
Sawtooth slope	Up Down
Range scale	3 to 1,800 yd 85 to 1,200 yd
Pinging provision	None
Listening provision	With RO-1 only (see text)
Signal indication	Loudspeaker and 5-in. CRO†
Driver amplifier output	Two 813, push-pull
Output	200 watts @ 42 kc
Projector	Brush C26 (vertical)
Hydrophone	Brush C26 (horizontal)
Physical assembly	Three 48-in. relay rack cabinets
Location	50-ft motor sailer, April 1942 M.V. *Torqua*, July 1942

* The symbols for oscillators are for identification only. The letters are the initials of the design and development engineers.

† This instrument was subsequently replaced by a specially built 7-in. long-persistence (P7 phosphor) oscillograph.

4.1.4 Cobar Mark IV

MODIFICATIONS

The Mark IV Cobar was constructed primarily to facilitate measurements of a laboratory nature and for this purpose was installed on a barge in San Diego Harbor. The receiver and driver amplifier were built by UCDWR for this model.

AURAL INDICATION

Target recognition was much improved by the use of a larger high-fidelity loudspeaker in place of the smaller limited-range speakers used on prior models.

FLYBACK BLANKING

In this system a discriminator-type blanker cut off both the receiver injection and the transmitter during flyback. Because of the frequency-sensitive nature this type of blanker anticipated the flyback interval by sufficient time to minimize interference.

DATA SHEET—*Cobar Mark IV*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	UCDWR
Type	Superheterodyne
Input filter	36-48 kc
Intermediate frequency	6 kc
Broad	1,000 c pass band
Sharp	300 c pass band
Audio output frequency	800 c
Bandwidth	100 c pass band
Sawtooth-modulated oscillator [SMO]	Hewlett-Packard Model 426
Sawtooth slope	Up
Range scale	30 to 3,000 yd

DATA SHEET—*Cobar Mark IV (Continued)*

Flyback blanking	Discriminator type
Pinging provision	Provided
Listening provision	42 kc ±
Broad	± 500 c
Sharp	± 150 c
Doppler correction	None
Signal indication	Loudspeaker and 5-in. Du Mont CRO
Driver amplifier output	Four 845, push-pull, parallel
Operation	Class A
Output	100 watts @ 42 kc
Projector	W.U. and/or C13*
Hydrophone	Eight Brush C13's*
Physical assembly	Four 72-in. relay rack cabinets
Location	Barge No. 2, February 1942 Barge No. 4, subsequently

* The projector and hydrophones were later replaced by Brush Co. C26's, improved crystal motors.

4.1.5

Cobar Mark V

Modifications

The Mark V Cobar equipment differed from all previous systems in that it could be operated with a carrier frequency of either 21 or 42 kc and used the Bell Telephone Laboratories SMO, Model No. X61907.

FMO

Mark V was used only 6 weeks and nearly the whole time was spent in adjusting the Bell Telephone Laboratories oscillator in an attempt to obtain satisfactory operation. Since no direct information could be obtained on the possible desirability of the 18- to 24-kc band versus the 36- to 48-kc band, the Mark IV system was reassembled. The account of subsequent work with this system is found under Mark VI. Listening was provided similar to that of Mark III. On the 21-kc carrier, the operator could listen simultaneously on two channels either 500 or 150 c wide, displaced ± 3 kc from the fixed frequency. On the 42-kc carrier the bands were 1,000 c wide and displaced ± 6 kc.

DATA SHEET—*Cobar Mark V*

Carrier frequency	21 kc	42 kc
Frequency sweep	± 3 kc	± 6 kc
Receiver	UCDWR	
Type	Superheterodyne	
Input filter	18-24 kc	
Intermediate frequency	3 kc	6 kc
Broad	500	1,000 c pass band
Sharp	150	300 c pass band
Audio output frequency	800 c	
Bandwidth	100 c pass band	
Sawtooth-modulated oscillator [SMO]	Bell Telephone Laboratories Model X61907	
Sawtooth slope	Down	
Range scale	25 to 2,800 yd	
Flyback blanking	None	
Pinging provision	None	
Listening provision	See text	
Doppler correction	None	
Signal indication	Loudspeaker and 9-in. CRO	
Driver amplifier output	Two 805, push-pull	
Operation	Class B	
Output	250 watts	
Projector	W.U. and/or C13	
Hydrophone	Eight Brush C13's	
Physical assembly	Five 72-in. relay rack cabinets	
Location	Barge No. 4	

4.1.6

Cobar Mark VI

Modifications

Since no data had been collected comparing 21-kc with 42-kc carrier frequency operation with the Mark V equipment, the Mark VI system was changed to operate at the lower frequency.

Receiver

An 18- to 24-kc band-pass filter replaced the 36- to 48-kc filter of the Mark IV receiver.

PROJECTOR-HYDROPHONE

In addition to the effective combination of two Brush Company C26's, horizontal and vertical, various other units were used both as projectors and hydrophones. Among these were the Mason prism (elements parallel), the RO-30-6, and the Submarine Signal Company type JK.

DATA SHEET—*Cobar Mark VI*

Carrier frequency	21 kc
Frequency sweep	± 3 kc
Receiver	UCDWR
Type	Superheterodyne
Input filter	18-24 kc
Intermediate frequency	3 kc
Broad	300 c pass band
Sharp	150 c pass band
Audio output frequency	800 c
Bandwidth	100 c pass band
Sawtooth-modulated oscillator [SMO]	Hewlett-Packard Model 426*
Sawtooth slope	Up
Range scale	30 to 3,000 yd
Flyback blanking	Sawtooth voltage used directly
Pinging provision	18 and 24 kc
Listening provision	21 kc
Broad	500 c pass band
Sharp	150 c pass band
Doppler correction	None
Signal indication	Loudspeaker and 9-in. CRO
Driver amplifier output	Two 805's, push-pull
Operation	Class B
Output	250 watts
Projector	W.U. 1, or Eight Brush C13's, or One Brush C26†
Hydrophone	Brush C26 (see text)‡
Physical assembly	Four 72-in. relay rack cabinets

* Modified to operate in the 18-24 kc band.

† Long axis vertical to produce a broad horizontal fan-shaped beam.

‡ Long axis horizontal to give a narrow beam in the horizontal plane.

4.1.7 Cobar Mark VII

MODIFICATIONS

Mark VII Cobar was constructed by UCDWR as a demonstration model for OSRD, Figure 2. It embodied all the principles thought to be satisfactory and practicable from prior investigation, including:

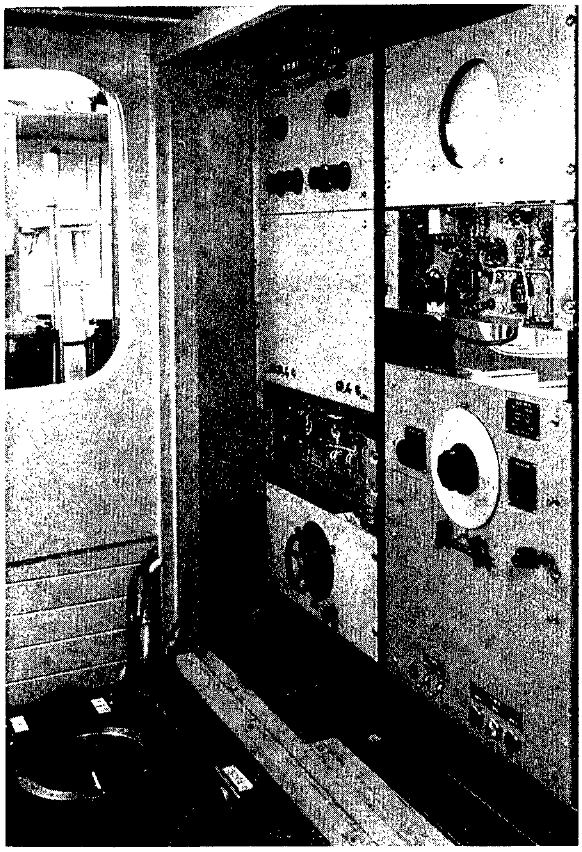


FIGURE 2. Cobar Mark VII (MV *Torqua* installation).

1. Regulated power supply, improved (low impedance from 1 c to 60 kc).
2. 21-kc operating band, 3 kc i-f.
3. Surge-type flyback blanking of oscillator.
4. Downsweep for simplicity and improved linearity.
5. Provision for automatic or hand-keyed pinging (permitting communication).
6. Preamplification in the receiver.

QC Type or Pinky[b] *Operation.* Two varistor

[b] Pinky is a contraction of Ping-Key.

circuits were provided for QC-type operation, one to blank the oscillator output during flyback of transmitted signal (ping) and one to blank the receiver during the transmission of the signal. A relay automatically performed the necessary switching sequence which reduced loudspeaker noise.

The same relay could be used as a key for supersonic communication between ships. A "pre-pinger" or anticipating circuit coupled to the sawtooth provided means for automatic sector scanning. A frequency-modulated ping or chirp feature enabled listening under conditions of high water noise.

DATA SHEET—*Cobar Mark VII*

Carrier frequency	21 kc
Frequency sweep	± 3 kc
Receiver	UCDWR new design
Type	Superheterodyne
Input filter	16-kc high pass
Intermediate frequency	3 kc
Bandwidth	300 c pass band
Audio output frequency	800 c
Bandwidth	100 c pass band
Sawtooth-modulated oscillator [SMO]	2 voltage sensitive oscillators, new design MC-2 and RO-1
Sawtooth slope	Down Down
Range scale	8 to 3,000 yd or 85 to 1,200 yd
Flyback blanking	Surge type
Pinging provision	24 kc
Listening provision	18 and 24 kc ± 3 kc
Doppler correction	None
Signal indication	Loudspeaker and 7-in. CRO
Driver amplifier output	Four 807, push-pull
Operation	Class AB
Output	50 watts
Projector	Brush AX7
Hydrophone	Submarine Signal Co. Type JK soundhead
Physical assembly	Two 32-in. relay rack cabinets
Location	Barge No. 4, M. V. *Torqua*

4.1.8 Cobar Mark VIII

MODIFICATIONS

The Mark VIII Cobar, the last system, was built completely by UCDWR and embodied most

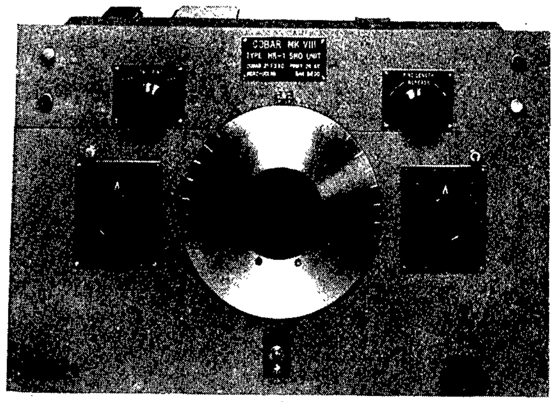


FIGURE 3. Cobar Mark VIII sawtooth-modulated oscillator Type MR-1.

of the desirable circuit features of previous Cobar designs (Figures 3 and 5). A Sigma sum-

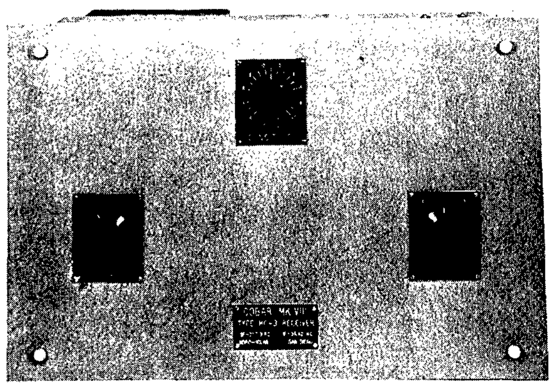


FIGURE 4. Cobar Mark VIII receiver Type MC-3.

frequency channel was added to the receiver to enable 42-kc operation.

RECEIVER

The Mark VIII receiver (Figure 4) used preamplification. In addition to the 3-kc i-f amplifier used with the Delta Cobar receivers the

Mark VIII provided a second i-f amplifier at 42 kc to facilitate Sigma operation. These i-f amplifiers were fed from corresponding filters at the output of the first ring modulator. The 42-kc Sigma signal was fed to a second ring modulator where it was heterodyned to 3 kc to make it analogous to the 3-kc Delta signal and facilitate indication.

A flexible switching arrangement permitted a target to be indicated aurally or visually by either Sigma or Delta operation or any combination of the two.

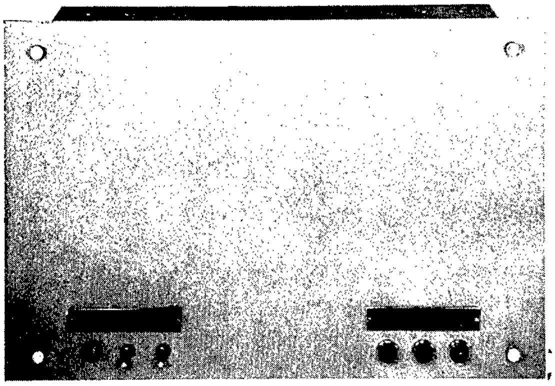


FIGURE 5. Cobar Mark VIII power supply.

DATA SHEET—*Cobar Mark VIII*

Carrier frequency	21 kc
Frequency sweep	± 3 kc
Receiver	New design for Mark VIII (MC-3R)
Intermediate frequency	3 kc
Audio output frequency	800 c
Sawtooth-modulated oscillator	MR-1 (voltage sensitive)
Sawtooth slope	Down
Range scale	10 to 3,000 yd
Flyback blanking	Surge type
Pinging provision	24 kc
Listening provision	18 or 24 kc ± 3 kc
Doppler correction	None
Signal indication	Loudspeaker and 7-in. CRO
Driver amplifier	Four 807, push-pull, parallel Two 838, push-pull
Projector	Brush AX7
Hydrophone	Submarine Signal Co. Type JK soundhead
Physical assembly	Two 48-in. relay rack cabinets
Location	1st unit to New London; 2nd unit M. V. *Torqua;* and components of 3rd to Barge No. 4

4.2 PRIBAR SYSTEMS

The Pribar developments marked the first attempt in early FM systems to scan range automatically. In essence, these systems were a single-channel Cobar with the necessary modifications to scan range and bearing simultaneously. The information appearing at the output of these systems was to be presented in the form of a folded plan position plot on a cathode-ray oscillograph whose persistence was the only means at that time of storing PPI information. (Pribar Marks II and III eliminated this feature.) Bearing scanning was accomplished by means of the Mason prism which was an acoustic grating with delay networks so connected that the bearing was proportional to frequency.

Range, which in Cobar was proportional to the slope of the sawtooth modulation, was scanned by a 20-c secondary modulation in the form of a sine wave. This secondary modulation applied only to the injection frequency used to heterodyne the received echo and this caused the difference frequency from a given target to vary through a frequency spectrum equal to the secondary modulation. It can be seen that all target echoes in the form of difference frequencies would then be swept past the particular point in the difference spectrum at which the Cobar i-f filter and amplifier responded. Thus, one indication was received from each target at the output of the i-f amplifier each time the range was swept (i.e., twice per cycle of the secondary 20-c modulating frequency).

The vertical sweep of the cathode-ray oscillograph, being controlled by the 20-c oscillator, had deflected to the proper range indication at the time the target indication was passed by the i-f amplifier. The intensity of the CRO was controlled by the amplitude of the target echo and normally operated below visibility when no target was present.

The operation of Pribar may be better understood if it is considered as an FM system in which the difference frequency is proportional to range. This difference frequency spectrum can now be considered analyzed by means of a filter scanned across it at a 20-c sinusoidal rate. In actual practice the filter operated at a fixed frequency and the signals appearing in the spectrum were caused to scan past the filter at this 20-c modulation rate.

One aspect which might be confusing is that the original heterodyning operation in the first mixer performed a dual purpose.

1. The comparison of the transmitted signal with the returning echo obtained the difference frequency and hence, the range of the target.

2. It swept this difference-frequency spectrum past the i-f filter by means of a 20-c modulation with an excursion of 3 kc.

It is not difficult to understand the cause of the folded bearing scale if consideration is given to the manner in which the horizontal sweep of the indicator is controlled and the way in which the Mason prism interprets the bearing of an echo.

1. The horizontal sweep of the CRO, which indicates the azimuth of the received echo, is connected to the same sawtooth voltage which controls the transmitted frequency.

2. The direction from which the Mason prism receives an echo is dependent only on the frequency of that echo. Remembering that the indicated azimuth is directly controlled by the frequency of the transmitted signal, consider the Mason prism to be a sharply directional hydrophone whose beam is controlled in azimuth by the frequency of the returning echo. Then, for a target at zero range, the indicated azimuth falls correctly on a linear scale with *no* displacement. As the range increases, however, the returning echo is delayed by the time necessary to travel out to the new target position and return. During this time the transmitted signal, hence the indicated azimuth, has moved on to a new position and the azimuth is in error proportional to this amount.

In actual practice the Pribar system was considered to be in focus when the target was at range such that the returning echo was delayed by an amount equal to one-half of the sawtooth cycle. This caused the effect referred to as "folding" of the azimuth scale since bearings near 000 appeared simultaneously at both edges of the indicator screen while bearings near 090 and 270 appeared near the center due to the time delay of one-half sweep.

4.2.1 Pribar Mark I

Modifications

The significant change over the Cobar systems, the attempted addition of a plan position plot, is discussed at length under Pribar Developmental Systems.

Visual Indication

Owing not only to the interference caused by the many frequencies present in Pribar but also to the variability of the transmission of sound through water and the constantly changing bearing error, it was almost impossible to interpret the indications obtained with Pribar Mark I. When this became apparent after thorough testing the system was abandoned in favor of the Mark II which made no attempt to present a plan position plot, operating more as a Cobar type with an oscillograph merely to assist in the azimuth indication.

DATA SHEET—*Pribar Mark I**

Carrier frequency	21 kc
Frequency sweep	± 3 kc
Receiver	Same as Cobar Mark V
Intermediate frequency	3 kc
Audio frequency	800 c
Sawtooth-modulated oscillator [SMO]	Two oscillators with common sawtooth. Hewlett-Packard 426 and duplicate for injection
Sawtooth slope	Up

DATA SHEET—*Pribar Mark I (Continued)*

Range scale	30 to 3,000 yd
Flyback blanking	Slope type
Pinging provision	None
Listening provision	None
Signal indication	Loudspeaker and 9-in. LP CRO
Driver amplifier output	Two 805, push-pull
Projector	Eight Brush C13's
Hydrophone	Mason prism
Physical assembly	Four 72-in. relay rack cabinets
Location	Barge No. 4

* This system did not function satisfactorily mainly because of the interference caused by two frequencies.

4.2.2

Pribar Mark II

MODIFICATIONS

Pribar Mark II used most of the equipment of Mark I but did not attempt to provide a PPI presentation. The only remaining differences between the two systems were that the SMO used in the Mark II had been changed to the Bell Telephone Laboratories Model X61907A, and the 20-c range-scanning sweep had been eliminated. This made the Mark II operation the same as Cobar with the exception that CRO was still connected to indicate bearing with the Mason prism under conditions of focus.

DATA SHEET—*Pribar Mark II*

Carrier frequency	21 kc
Frequency sweep	± 3 kc
Receiver	Same as Cobar Mark V
Intermediate frequency	3 kc
Audio frequency	800 c
Sawtooth-modulated oscillator [SMO]	Bell Telephone Laboratories Model X61907A
Sawtooth slope	Down
Range scale	25 to 2,800 yd
Flyback blanking	None
Pinging provision	None
Listening provision	None
Doppler correction	None
Signal indication	Loudspeaker and 9-in. CRO
Driver output stage	Two 805, push-pull
Projector	Brush C26
Hydrophone	Mason prism
Physical assembly	Five 72-in. relay rack cabinets

4.2.3

Pribar Mark III

MODIFICATIONS

Pribar Mark III, Figure 6, was the same as Mark II with the exception of the SMO, the

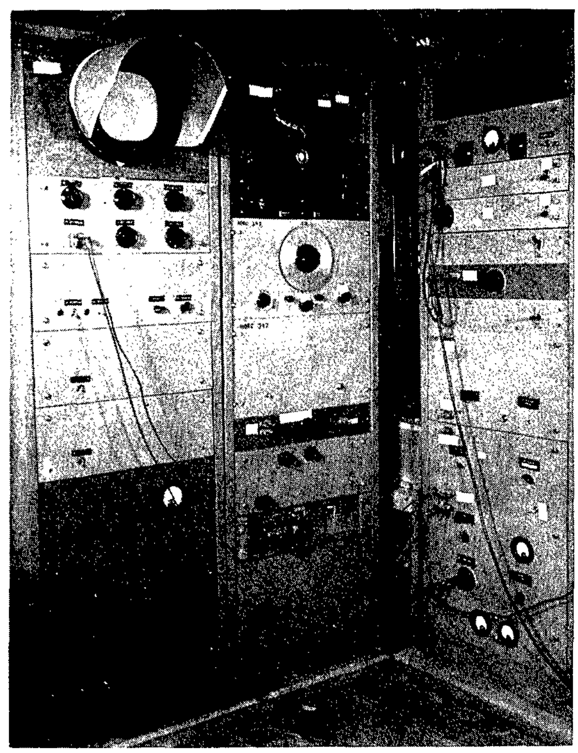


FIGURE 6. Pribar Mark III three (of four) rack cabinets (UCDWR Barge No. 4 installation).

Hewlett-Packard 426A being used with this equipment.

DATA SHEET—*Pribar Mark III*

Carrier frequency	21 kc
Frequency sweep	± 3 kc

DATA SHEET—*Pribar Mark III (Continued)*

Receiver	Same as Cobar Mark V
Intermediate frequency	3 kc
Audio frequency	800 c
Sawtooth-modulated oscillator [SMO]	Hewlett-Packard 426A
Sawtooth slope	Up
Range scale	30 to 3,000 yd
Flyback blanking	Slope type
Pinging provision	None
Listening provision	None
Doppler correction	None
Signal indication	Loudspeaker and 9-in. CRO
Driver amplifier output	Two 805, push-pull
Projector	Brush C26
Hydrophone	Mason prism
Physical assembly	Four 72-in. relay rack cabinets
Location	Barge No. 4

4.3 SUBSIGHT DEVELOPMENTAL SYSTEMS

Subsight was designed for antisubmarine warfare fire control. The systems were compact and simplified versions of Delta Cobar with the exception that various controls were provided to compensate for variables encountered in this application.

Theory of Range-Rate Compensation

When properly adjusted these devices were capable of furnishing time-to-fire data for ahead-thrown antisubmarine weapons, automatically compensating for range-rate error. The magnitude of the doppler-induced range error is a function of two parameters, the average frequency of the transmission band and the amplitude of the frequency excursion, while the sign of the error depends on whether the sweep is up or down.

Expressed mathematically, the basic equation for range in this type of sawtooth frequency-modulated system is:

$$R_s = R_{sc}\left[1 + \frac{2v}{V}\left(\frac{f}{\Delta f}\right)\right] \tag{1}$$

where R_s = actual slant range between searching vessel and target at instant of firing;
R_{sc} = actual slant range at instant of exploding;
$v = V_D - V_s$, relative velocity of the destroyer and submarine; where
V_D = velocity of destroyer, 6 yd per sec, (= 10.5 knots); and V_s = velocity of submarine, 3 yd per sec, (= 5.2 knots); (V_s is the component in the *line of sight* of the submarine's true velocity);
V = velocity of sound in water;
f = average frequency of transmitted signal;
Δf = maximum deviation, or excursion, of the transmitted frequency from its average value.[c]

This equation is true for only one value of $f/\Delta f$, and that is the value that must therefore be used for velocity and depth compensation. The final term in the above expression gives the shift in range resulting from the doppler effect. When $v = 0$ this term is obviously zero and $R_s = R_{sc}$. By proper choice of $f/\Delta f$ the value of this term may be made such that R_s exceeds R_{sc} by any desired percentage per knot of relative speed v.

Solving equation (1) for $f/\Delta f$

$$\frac{f}{\Delta f} = \frac{(V/2)\,R_s - R_{sc}}{R_{sc}\cdot V} \tag{2}$$

but $(R_s - R_{sc})/V = T$ almost exactly,[d] and thus

$$\frac{f}{\Delta f} = \left(\frac{V}{2}\right)\left(\frac{T}{R_{sc}}\right) \tag{3}$$

and

$$R_{sc} = \left(\frac{R_E - V_D\,T_b}{\cos\theta_2}\right) \tag{4}$$

which may be written

$$R_{sc} = R_E - V_D\,T_b + D^2 \text{ yards}/600 \tag{5}$$

[c] This is also the frequency of the signal obtained by heterodyning the received echo with a wave having the frequency of the transmitter under the condition of range focus.

[d] The exact expression is $R_s \cos\theta_1 - R_{sc}\cos\theta_2 = vt$, where θ_1 = the angle the slant range R_s makes with the horizontal.

where T_a = time of flight of projectile in air (= 8 sec);
T_b = time of sinking in water (approx. 9 sec to 200 ft);
$T = T_a + T_b$, total projectile travel time;
R_E = the base range, assumed equal to 300 yd;
D = assumed depth of submarine (= 200 ft);
θ_2 = angle the slant range, R_{sc}, makes with the horizontal.

From equations (3) and (5) a table of pairs of values of $f/\Delta f$ and R_{sc} that yield compensation at any desired depth may be calculated.

The following achievements were made possible by the Subsight systems.

1. Using Mark VII Cobar as a Subsight with a subcaliber mousetrap installation, 36 single-salvo attacks on artificial targets, 23 on a 40x12-ft armored target motorboat, and 4 on a submarine were made. On the artificial target of submarine dimensions 50-per cent hits were recorded by observation and photography. One direct hit and two near misses marked the motorboat attacks.

2. Mark V Subsight easily located a sunken seaplane containing valuable recording equipment and records at the bottom of Lake Mead (Boulder Dam).[21]

3. Mark 13 (bottom) mines[1] were detected 50 per cent of the time at about 200 yd over a hard bottom under poor sonic conditions. The percentage rose to almost 100 with ranges over 400 yd under good sonic conditions. Moored mines were detected with such assurance at Norfolk, Va. tests that the program for use of FM sonar systems for mine detection was initiated.

4.3.1 Subsight Mark I

Modifications

The Mark VII Cobar system was adapted for the first studies of this fire-control device and became known as Subsight Mark I.

Range-Rate Compensation

The sawtooth-modulated oscillator swept down and thus indicated targets at greater than actual range with closing range rates. This was not the condition desired but since automatic range-rate compensation had not been developed when this system was first tested, range-rate corrections were made by manual adjustment of the range dial according to calculations.

DATA SHEET—*Subsight Mark I*

Carrier frequency	21 kc
Frequency sweep	± 3 kc
Receiver	Cobar Mark VII
Intermediate frequency	3 kc
Audio output frequency	800 c
Sawtooth-modulated oscillator [SMO]	RO-1
Sawtooth slope	Down
Range scale	85 to 1,200 yd
Flyback blanking	Surge type
Doppler error per knot	0.47%
Signal indication	Loudspeaker
Driver amplifier	Four 807's push-pull, parallel
Projector	Brush AX-7
Hydrophone	Brush C26
Physical assembly	One 48-in. relay rack cabinet
Location	M.V. *Torqua*

4.3.2 Subsight Mark II

Modifications

Subsight Mark II was planned to be a compact assembly patterned in circuit design after the Cobar Marks VII and VIII. It was planned to include the receiver, SMO, and driver amplifier in one cabinet. Forty-two kc was retained as the operating carrier frequency.

Discontinuation

This system had scarcely entered the breadboard developmental stage when automatic range-rate compensation was discovered. Because of the design parameters required for automatic compensation, the Mark II unit was discontinued while still in the experimental stage.

DATA SHEET—*Subsight Mark II*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	New design
Intermediate frequency	6 kc
Audio output frequency	800 c
Sawtooth-modulated oscillator [SMO]	MR-2
Sawtooth slope	Down
Range scale	100 to 600 yd
Flyback blanking	None
Doppler error per knot	0.47%
Signal indication	Loudspeaker, relay
Driver amplifier output	Two 6L6, push-pull
Projector	Brush C26
Hydrophone	Three Brush C13
Physical assembly	One 8¾-in. standard rack panel

4.3.3

Subsight Mark III

Modifications

Subsight Mark III was initiated at the same time as Mark II and was to be little different from Mark II. It was the opinion of some of those who were involved in the work at this time that greater power amplifier output was likely to be needed to overcome attenuation and ship noise. Accordingly, the Mark III was designed with a 25-watt driver amplifier instead of the 15-watt unit used in Mark II. This modification required that the Mark III system occupy approximately twice the size cabinet as the Mark II.

Discontinuation

In all other respects the Mark III closely resembled Mark II in proposed design. It was discontinued while still in the breadboard experimental stage for the same reasons as mentioned for Mark II.

DATA SHEET—*Subsight Mark III*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	New design
Intermediate frequency	6 kc
Audio output frequency	800 c
Sawtooth-modulated oscillator [SMO]	MR-3
Sawtooth slope	Down
Range scale	100 to 600 yd
Flyback blanking	Surge type
Doppler error per knot	0.47%
Signal indication	Loudspeaker, relay
Driver amplifier output	Four 6L6, push-pull, parallel
Projector	Brush C13
Hydrophone	Brush C13
Physical assembly	One 17½-in. standard rack panel

4.3.4

Subsight Mark IV

Modifications

Subsight Mark IV consisted for the most part of Cobar Mark VII equipment with the exception of the WP-1 SMO, which could be given an up or down sweep as selected by the operator at either 21- or 42-kc carrier, and minor changes in the receiver.

Projector-Hydrophone

A special unit, the GB-1 built by the UCDWR, combined two X-cut Rochelle salt transducers each approximately 4x8 in., in a common case. This unit was supplemented during some of the tests by a Brush AX-7 projector and a Submarine Signal Company Type JK hydrophone.

DATA SHEET—*Subsight Mark IV*

Carrier frequency	42 kc
Frequency sweep	± 2 kc
Receiver	Modified Cobar Mark VII
Intermediate frequency	2 kc
Audio frequency output	800 c
Sawtooth-modulated oscillator [SMO]	WP-1
Sawtooth slope	Up or down as selected by operator
Range scale	100 to 1,200 yd
Flyback blanking	None
Doppler error per knot	± 1.4% (up); —1.4% (down)

DATA SHEET—*Subsight Mark IV (Continued)*

Optimum target depth	Surface (up) None (down)
Signal indication	Loudspeaker
Driver amplifier	Four 807, push-pull, parallel
Projector	GB-1 (½ split 8x8 in.) or 1 AX-7
Hydrophone	GB-1 (½ split 8x8 in.) or JK
Physical assembly	One 48-in. standard relay rack
Location	M.V. *Torqua*

4.3.5 Subsight Mark IV-A (or "IV½")

Modifications

The Mark IV-A system was an heterogeneous assembly of parts of Cobar Marks III and VII assembled at New London by UCDWR at the request of Columbia University, Division of War Research.

Projector-Hydrophone

A second GB-1 unit failed to function inside a QBE-1 streamline dome because of high inter-unit coupling (crosstalk). Results were poor later due to too many modifications and adaptations in the system.

4.3.6 Subsights Mark V and VI

Modifications

Subsights Mark V and VI (Figure 7) differed from earlier Cobar and Subsight systems in the three following respects: (1) automatic firing or firing-time indicator switch for antisubmarine ordnance projectiles, (2) automatic range-rate compensation by means of an up sawtooth, (3) compact single chassis construction.

Velocity Compensation

The Mark V velocity-compensated Subsight gave a firing indication to the control officer at the target range which was automatically corrected for range rate and projectile flight time in an attack on a surface target. The Mark VI supplied the same type of information plus an additional correction for an attack on a target at 100-ft depth.

While the range-rate compensation can correct completely for all errors and delays encountered in range, no automatic correction for azimuth and no information regarding target depth is given by these units.

DATA SHEET—*Subsights Mark V, VI*

Carrier frequency	Mark V 42 kc	Mark VI 60 kc
Frequency sweep	± 2 kc	± 2 kc
Receiver	New design for these systems	
Intermediate frequency	2 kc	
Audio output frequency	800 c	
Sawtooth-modulated oscillator [SMO]	MR-4	
Sawtooth slope	Up	
Range scale	100 to 600 yd	
Flyback blanking	Partial (2nd detector)	
Doppler error per knot	± 1.4 per cent; + 2.0 per cent (resp.)	
Optimum depth of target	Surface; 100 ft (respectively)	
Signal indication	Loudspeaker, relay	
Driver amplifier output	Two 6L6, push-pull	
Output	15 watts	
Projector	GB-1; CH-10*	
Physical assembly	Submarine Signal Company No. 755 receiver cabinet (11x22x16 in.)	
Physical location	1 Unit, Mark V, M.V. *Torqua* 1 Unit, Mark V, WCSS vessel *Gitana* 1 Unit, Mark VI, New London, Conn. (Two Mark V's), USNMWTS, Solomons, Md. Service Squadron Five YMS 79, Norfolk, Va.	

* GB-1 has an 8x8-in. X-cut Rochelle motor. CH-10 has a 2x4-in. Y-cut Rochelle motor. Both motors are made up of two electrically independent halves, 1x8 in. and 2x2 in., respectively.

4.4 FAMPAS SYSTEMS

The Fampas[19] system offered a radical change in the existent Cobar concept and methods of operation. The new system presented continuous bearing and range information on a cathode-ray oscillograph screen. The horizontal axis x of the cathode-ray tube was calibrated in azimuth, the vertical axis y in range, while signal intelligence was applied to the intensity electrodes z axis.

The Fampas system was an FM equipment utilizing individual signal energy storage in multiple channels to permit: (1) the averaging of the signal present in these channels, (2) the rapid scanning of the information obtained from each of these channels, and (3) the elimination of range ambiguities.

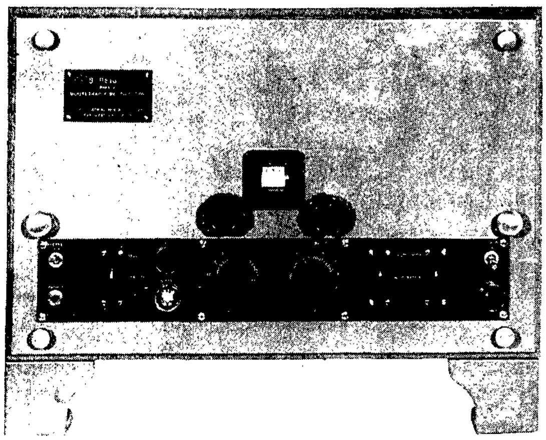


FIGURE 7. Subsight Marks V and VI.

By retaining the signal averaging characteristic inherent in Delta Cobar operation, Fampas had the advantage of the high signal-to-noise ratio of the former system. Since successive signals on pinging systems are known to vary in amplitude by 20 db or more, this averaging characteristic was a prerequisite.

While a Delta Cobar system must remain focused on one spot for a period of time long enough to secure a statistical average of the signal from that spot, a system providing a method of integrating or storing the signal energy received from various spots could scan rapidly. Fampas had this marked advantage.

The method of eliminating range ambiguities consisted primarily of choosing the transmission frequency-time relationship (rate of frequency sweep) so that the received signals lay close to the transmitted frequencies. These ambiguities due to image frequencies in the system were made to fall outside the receiver difference-frequency pass band (0 to 3 kc) except for ranges beyond 7,400 yd and at these extreme ranges an adequate signal path presumably rarely existed. The fraction of each sawtooth cycle occupied by the unwanted image frequencies introduced a loss of time proportional to the range. This lost time was not a serious difficulty as it represented merely some degradation of resolution at extreme ranges, becoming insignificant inside 1,000 yd.

If we consider an FM system of the Cobar type in which the carrier was modulated with a sawtooth wave, it is obvious that: (1) the time-frequency relationship of this sawtooth modulation had the effect of converting range information into a frequency spectrum, (2) this spectrum of range information was continuously present because of the nature of the transmission, and (3) this spectrum was further subdivided into a finite number of channels in which energy from spots or zones corresponding to different ranges could be stored. The storage or integration function could then be accomplished by rectifying the output of the individual channels and applying it to an RC network whose time constant was such that the voltage decay occurring between scanning periods would not be appreciable. This d-c output of the individual channels could then be scanned rapidly while the individual channels were continuously averaging the signal present in them.

The following achievements were made possible by the Fampas systems.

1. The Fampas equipment was able to depict echo-reflecting objects within sonic range in a complete oscillograph picture of the surrounding underwater area.

2. In addition to giving a pictorial representation of the surrounding underwater area the Fampas systems provided a means of scanning this area *rapidly*.

3. The discovery and evaluation of the relation between target echo strength and range (within a single maximum range setting of the FM system) and between target echo strength and maximum range setting of the FM system led to the employment of slope amplification tied to maximum-range adjustment in the system.

4. Two successful mousetrap attacks were made against a submarine and the sub was followed throughout a series of evasive maneuvers. Navigational experiments showed the equipment to be effective in locating a harbor antisubmarine net, shorelines, moored and drifting triplanes and polyplanes, as well as in differentiating between types of targets, seaweed, wakes, etc.

4.4.1 Fampas Mark I

Modifications

Most of the equipment used in the early trials of Fampas was borrowed from earlier Cobar and Pribar systems with modifications as proved necessary for the tests. The addition of a multichannel filter and electronic switch was the only new equipment needed. The multichannel filter was patterned after the acoustic analyzer in use at the David Taylor Model Basin and the output of this analyzer was scanned by an electronic switch developed at UCDWR.[2]

Receiver

Few modifications were necessary in the receiver, the major one being that of replacing the sharply tuned i-f channel with a 2,500-c low-pass filter to permit the broad-band operation necessary for multichannel reception.

Analyzer

The analyzer consisted of 10 channels, each tuned to overlap the adjacent channels at the 3-db down points. The bandwidths of these filters increased proportionately with the frequency passed (i.e., the 250-c filter was 52 c wide while the 2,000 was 458). The gains of the filter channels were individually adjustable to compensate for attenuation and divergence of echo strength as a given target was moved throughout one range scale. The range scale of the CRO that was given by this filter arrangement was logarithmic with resolution a constant fraction of the indicated range.

The electronic switch formed a synchronous commutator which scanned the output of each filter channel for possible stored energy. The scanning cycle of the commutator was synchronized with the logarithmic vertical range trace of the CRO by a pulse at 1/120-sec intervals. This pulse was developed from the 60-c line frequency.

Indicator

The magnetic deflection coils used with the Pribar system proved to have insufficient high-frequency response to retrace in one interchannel period. The effect, that of smearing channels 1 and 10, was ultimately eliminated by sacrificing the normal operation of channel 10 and devoting this time to the retrace.

Projector and Hydrophone

The GB-11 projector unit had a broad major lobe approximately 40 degrees wide within which the sound pressure was reasonably constant. The EB-2-1 hydrophone was highly directional, having a major lobe only about 8 degrees wide. Both units were hand-trained as a unit in the desired direction. It was found possible to obtain a very useful picture even while the hydrophone was being scanned at approximately 40 degrees per second.

It was discovered that the coupling and/or amplification of the transmitted signal through the receiving system prior to detection caused an objectionable modulation of the received echo. This effect was greatly reduced not only by the separation of the hydrophones but also by the elimination of preamplification of the carrier frequency.

DATA SHEET—*Fampas Mark I*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	Cobar Mark IV
Difference frequency band used	225 to 2,250 c
Number of analyzer channels	10

DATA SHEET—*Fampas Mark I (Continued)*

Bandwidth of analyzer channels	⅓ octave
Distribution of analyzer channels	Logarithmic
Audio output	Selected individual channels of composite receiver output
Signal indication	CRO, range vertical, bearing horizontal, intensity modulated by signal
Sawtooth-modulated oscillator [SMO]	Hewlett-Packard 426-A
Sawtooth slope	Up
Blanking	Pulse type
Range scales	Adjustable 180 to 1,850 yd
Driver amplifier	Two 805, push-pull
Output	200 watts
Projector	GB-11-1
Hydrophone	EB-2-1
Physical assembly	Three 72-in. standard rack cabinets
Location	Barge No. 4, February 1943

4.4.2 Fampas Mark II

Modifications

Two major changes characterized the Mark II Fampas equipment. These were the further subdivision of the spectrum from 10 to 20 channels, and the subsequent alteration from Cartesian to polar coordinates in providing a CRO plan position indication.

The Mark II was constructed with the basic idea of reducing the physical size of the system by a factor of three (i.e., one 72-in. cabinet) as well as improving its performance wherever possible.

Receiver

A new receiver was designed for Fampas Mark II. The essential difference between this receiver and that used with the Mark I equipment was that the preamplifier was omitted.

A ring modulator was used as first detector and the gain of the amplifier was adjusted to equalize[c] the echo strength received from a given target located within the limits of any one of the three range scales. This condition was approximated by a sloped gain characteristic of 12 db per octave to offset the combined effects of attenuation and divergence.

Visual Indication

The circuit that was developed to give a PPI provided a radial sweep and full 360-degree indication. The sweep direction was controlled by the then relatively new device known as a sine potentiometer coupled to the hydrophone column. Substantially the same circuit is still used in the QLA sonar gear.

SMO

Several minor modifications were made in the SMO, one of these being a change in the source of regulated voltage for the sawtooth voltage generator. Another was in the blanking circuit where the pulse-operated varistor was replaced by a thyratron which was arranged to fire just before the normal sawtooth flyback. A negative pulse obtained from this tube's operation served to cut off the push-pull SMO output stage.

Projector and Hydrophone

The CA-1, a 360-degree projector designed for use with the polar coordinate system, provided complete irradiation of the water around the ship at all times. This unit was extravagant in both crystals and power. The EB-2-1 hydrophone used in this combination was highly directional but could be trained automatically through 360 degrees or narrow-scanned in a controllable sector for continued investigation of a given target.

DATA SHEET—*Fampas Mark II*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	New type
Gain	Sloped (12 db/octave)
Preamplifier	None

[c] Note that this equalization of the difference frequencies is equivalent to range-varied gain in pinging systems.

DATA SHEET—*Fampas Mark II (Continued)*

Difference frequency band used	225 to 2,250 c
Number of analyzer channels	20
Bandwidth of analyzer channels	1/6 octave
Distribution of analyzer channels	Logarithmic
Audio output	Loudspeaker connected to any selected channel or the total receiver output
Signal indication	Cartesian plot first, replaced by a polar plot PPI later
Sawtooth-modulated oscillator [SMO]	RO-2
Sawtooth slope	Down
Range scales	430, 860, and 1,720 yd (maximum)
Driver amplifier	Two 838, push-pull
Output	250 watts
Projector	GB-11-1, CA-1
Hydrophone	EB-2-1
Physical assembly	One 72-in. standard rack cabinet
Location	Barge No. 4, April 1943 M.V. *Torqua*, June 1943

4.4.3 Fampas Mark III

MODIFICATIONS

The Mark III Fampas consisted for the most part of the same equipment found in the Mark II system with the exception of the analyzer section. The analyzer, consisting of ten channels, was modified Mark I gear with the frequency distribution of the filters changed from logarithmic to linear. Each filter now had a 70-c bandwidth and the pass bands were distributed linearly from 600 to 1,300 c.

This high resolution system was designed as a protective warning device for use in merchant vessel screening but was discontinued in favor of FM sonar.

ANALYZER

During experimentation with this system, the design of the analyzer was changed to use series rather than shunt switching. This change not only improved operation but allowed a 50 per cent reduction in the number of switching tubes required.

DATA SHEET—*Fampas Mark III*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	Same as Fampas Mark II
Difference frequency	600 to 1,300 c
Number of analyzer channels	10
Bandwidth of analyzer channels	70 c
Distribution of analyzer channels	Linear
Audio output	Composite receiver output spectrum
Signal indication	Same as Fampas Mark II, PPI
Sawtooth-modulated oscillator [SMO]	Same as Fampas II, PPI
Sawtooth slope	Down
Range scales	Adjustable for experiment
Driver amplifier	Two 838, push-pull
Projector	CA-1
Hydrophone	EB-2-1
Physical assembly	Three 24-in. relay rack cabinets
Location	M.V. *Torqua*, August 1943

4.5 FM SONAR SYSTEMS

The name sonar was accepted by the Navy in 1943. The Fampas equipment was therefore renamed FM sonar to conform to the new nomenclature for PPI systems. This was later redesignated QLA sonar by the Navy and the first fourteen systems produced were given the title of XQLA.

The first FM sonar equipment was very much like the previously discussed Fampas systems in design and construction. Three major new developments were incorporated, however.

1. The use of a series switching arrangement in the analyzer reduced the tube complement by about one-half (30 tubes).

2. An improved detector circuit for each channel automatically adjusted the threshold to permit optimum detection in the presence of reverberation.

3. A linear distribution of filter channels each 75 c wide, extended from 500 c to 2,000 c. FM sonar was the first system to incorporate the high resolution (narrow-filter channels) inherent in the Fampas Mark III system over a band this wide.

The following achievements were made possible by the FM sonar systems.

1. Using the UCDWR-built transducer CP-8, a submarine was spotted and tracked to a range of 3,000 yd. On an overside LCM mounting the equipment proved efficacious in locating buoys, sunken LCM's, shorelines, and scaffolding except in the presence of surf. Range and bearing of underwater explosion-disturbed areas could be detected through a strong negative thermal gradient in the presence of a ship's wake.

2. Naval personnel of both ComSubPac and ComServRon Five familiar with tactical problems of combat were favorably impressed by field and test demonstrations of the equipment as a navigational aid, mine detector, and as a prosubmarine and antisubmarine warfare device.

3. Mechanical and electronic conditions needing correction to make the equipment substantial enough for combat service were determined by actual test.

Needed for all installations:

a. A better, more powerful hoist-train mechanism.
b. A reinforced transducer design.
c. A heavier and more serviceable chassis construction.
d. A more rugged cabinet.
e. Forced air circulation.
f. More conservatively rated components.
g. A better impregnating compound, or hermetically sealed components.
h. A more convenient cable to chassis connection.
i. Illumination of the bearing scale.

Needed for submarine installations only:

a. A projector uptilt of approximately 5 degrees to provide better presentation of surface targets.
b. A reduction in the operating frequency (52 to 68 kc) to provide a broader vertical beam pattern for detecting surface targets.
c. A hydrophone constructed to provide a broad vertical beam pattern while retaining the narrow horizontal beam pattern.
d. The elimination of certain mechanical difficulties, slip rings, gear backlash.

4.5.1 FM Sonar Model 1, No. 1

Modifications

Basically, the FM Sonar Model 1, No. 1 was an improved Fampas modified to include all of the circuit refinements of prior developments. See Figures 8, 9, 10, and 11.

Receiver

A completely new receiver was designed for this system, having greater amplification than any other previous model. Since this system was designed particularly for submarine detection at long ranges, this additional amplification was necessary. Dual output stages were provided, one to drive the analyzer filters, the other the loudspeaker.

Analyzer

The new 20-channel analyzer covered the audio spectrum in 75-c increments linearly from 500 to 2,000 c. This feature had the dual capability of providing greater range resolution and accuracy. A newly designed 20-point electronic switch was also included.

A third significant feature added was the reverberation-controlled threshold to make the detector circuit sensitive to input changes of moderately short duration only. An RC network in the grid return of the detector was coupled to its cathode in such a manner that the input signal controlled the bias. For signals of long duration the voltage developed across the cathode resistor had sufficient time to charge the RC network condenser, increasing the bias and, therefore, decreasing the effect of the signal.

This arrangement allowed the use of higher receiver gains without permitting reverberation to light the CRO screen, i.e., the sensitivity was made higher to desired signals.

Sawtooth-Modulated Oscillator [SMO]

Four different reticles were furnished for use with the two types of sawtooth-modulated oscillators supplied. The 1U (upsweep) oscillator provided the subsight form of time-to-fire compensation for two possible keel depths of submarines, 120 and 200 ft. The two corresponding reticles were calibrated for an own-ship's speed of 10 knots, but a correction factor indicated proper time to fire at any practical speed. The remaining two for use with the 1D were engraved to provide a doppler-corrected indication for two speeds, 10 and 15 knots.

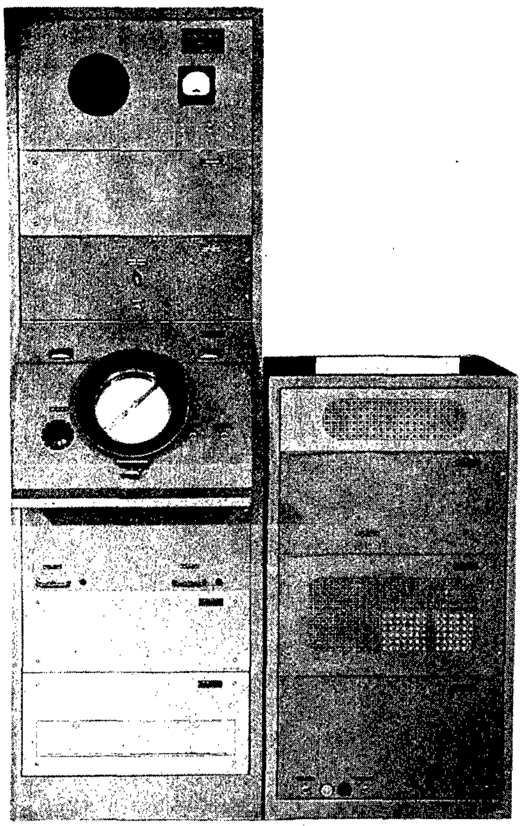


Figure 8. FM sonar Model 1, No. 1, Alt.0 (left, electronic stack; right, driver amplifier) USS *Semmes* installation, New London, Conn.

Visual Indication (See Figure 11)

The major improvement in the PPI scope was made in the clamping circuit. The gas tube previously used in Fampas Mark II was replaced by a "hard tube" diode circuit.

Projector-Hydrophone

The projector used during most of the tests aboard the *Semmes* was known as the CP6-1. This unit had a major lobe whose angular width was approximately 220 degrees. It was mounted on a modified hoist-train mechanism so as to remain in a fixed position with the nonradiating portion pointed aft.

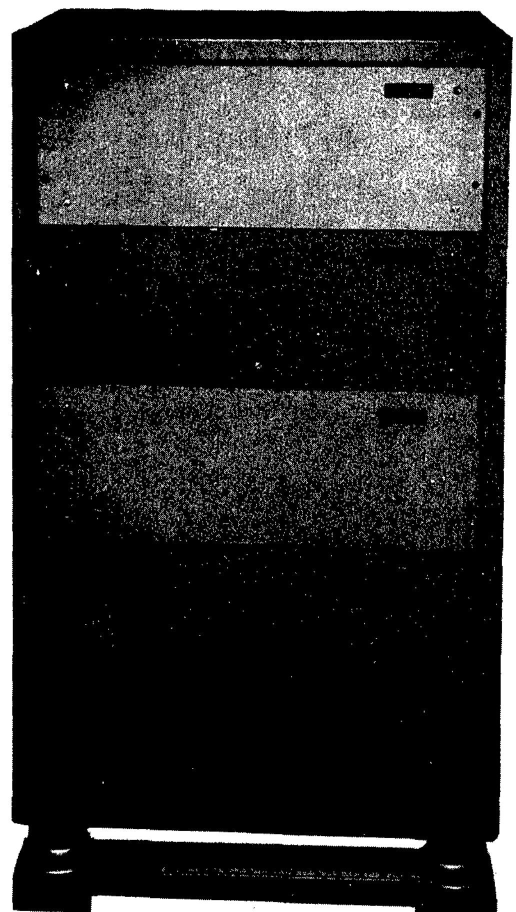


Figure 9. FM sonar Model 1, No. 1, Alt.3 (stack, receiver, oscillator analyzer) YMS 303 installation, Mediterranean area.

The hydrophone GC2-1 had a major lobe approximately 12 degrees wide at the average frequency of reception. The hydrophone was trainable through 360 degrees by the 1½-horsepower

motor that was part of the regular hoist-train equipment.

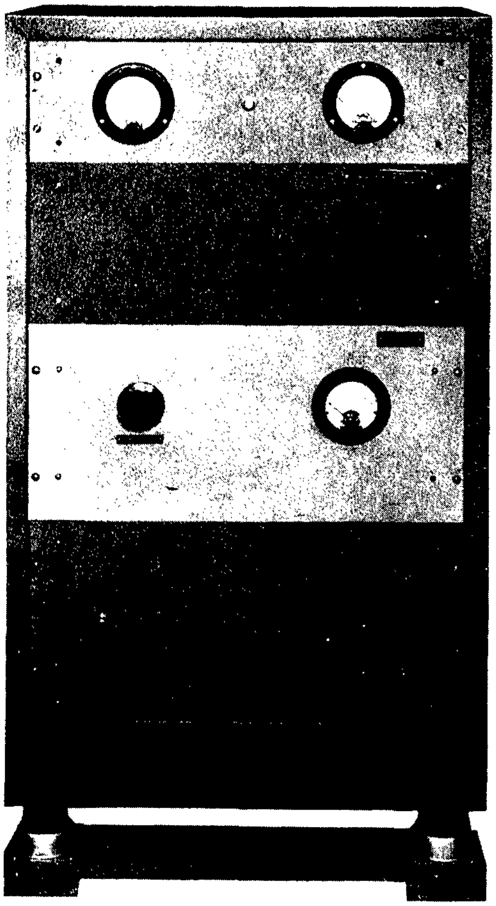


FIGURE 10. FM sonar Model 1, No. 1, Alt.3 driver amplifier and power supplies (YMS 303 installation, Mediterranean Area).

DATA SHEET—*FM Sonar Model 1, No. 1*

Carrier frequency	28 kc	
Frequency sweep	± 3½ kc	
Receiver	New design	
Difference frequency band	500 to 2,000 c	
Number of analyzer channels	20	
Bandwidth of analyzer channels	75 c	
Distribution of analyzer channels	Linear	
Audio output	Composite spectrum	
Signal indication	Improved PPI and loudspeaker	
Sawtooth-modulated oscillator [SMO]	1U	1D
Sawtooth slope	Up	Down
Range scales	Adjustable for experiment	
Driver amplifier	Four 838, push-pull, parallel*	
Projector	CP4-CP6	
Hydrophone	GC2-1	
Physical assembly	One 72-in. rack cabinet† One 36-in. rack cabinet	
Location	Barge No. 4, San Diego, Cal. USS *Semmes*, New London, Conn. Fort Pierce, Fla. YMS 303, Mediterranean area	

* Driver amplifier designed to deliver 500 watts was used in tests at San Diego and aboard the *Semmes*. Later unit delivered 250 watts.

† Equipment repackaged in two 48-in. relay rack cabinets for Mediterranean tests.

4.5.2 FM Sonar Model 1, No. 2

MODIFICATIONS

The Model 1, No. 2 FM sonar was essentially the same as the original Model 1, No. 1. It was installed aboard the MV *Torqua* to serve as a demonstration unit for visitors to the San Diego Laboratory.

ANALYZER

Since the mine investigation program required higher gain settings, unwanted or spurious signals were amplified and spotty indications on the cathode-ray screen resulted. Continued study of these spurious signals showed the majority of them to be of short duration, shrimp crackles, etc. Increasing the storage capacity of the condenser in the output of the detector made the system most sensitive to signals of about 0.3 sec duration. Longer and shorter durations were discriminated against.

SAWTOOTH-MODULATED OSCILLATOR [SMO]

The oscillator was the same unit as was previously used with Fampas Marks II and III as well as FM sonar Model 1, No. 1. An attempt was made, however, to minimize the effect of the blank or lost time period at the beginning of each cycle. The synchronization of the modu-

lation period with the oscillation of the hydrophone across its 90-degree arc of scan to place the start of the sawtooth at the extreme edges (i.e., at reversal) greatly reduced the effect.

PROJECTOR-HYDROPHONE

The CP5 projector used was a new experimental unit built by UCDWR. The hydrophone was, however, the same unit which had been used with the Fampas Mark I. The major lobe was approximately 8 degrees in the operating band.

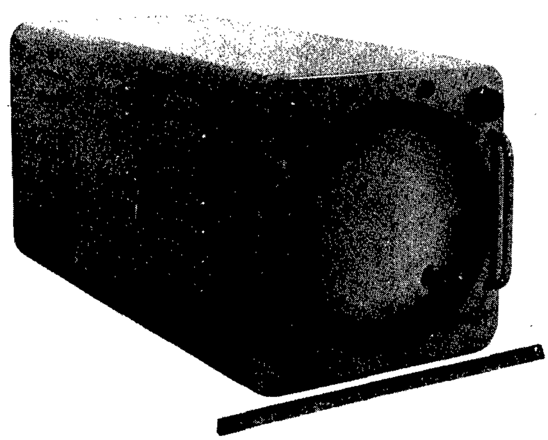


FIGURE 11. FM sonar Model 1, No. 1, Alt.3 indicator unit (YMS 303 installation, Mediterranean area).

DATA SHEET—*FM Sonar Model 1, No. 2*

Carrier frequency	42 kc
Frequency sweep	± 6 kc
Receiver	Same as FM sonar Model 1, No. 1
Difference band used	500 to 2,000 c
Number of analyzer channels	20
Bandwidth of analyzer channels	75 c
Distribution of analyzer channels	Linear
Audio output	Composite receiver spectrum
Signal indication	Improved PPI, loudspeaker
Sawtooth-modulated oscillator [SMO]	RO-2
Sawtooth slope	Down
Range scales	Adjustable for experiment
Driver amplifier	Two 838, push-pull
Operation	Class B
Output	250 watts
Projector	CP5
Hydrophone	EB2-1
Physical assembly	One 72-in. rack cabinet One 24-in. rack cabinet
Location	MV *Torqua*

4.5.3 FM Sonar Model 1, No. 3

MODIFICATIONS

The principal changes involved in Model 1, No. 3 were physical, brought about by the reduced space considerations for submarine mounting. The operating frequency band was raised to 52 to 68 kc, however, to gain security and improve hydrophone directivity.

VISUAL INDICATION

The basic circuit of the PPI scope was the same as the FM sonar Model 1, No. 1 but the high-voltage power supply only was retained in the indicator chassis. The low voltage regulated and unregulated supplies were now furnished from a separate supply in the stack. All operating controls were on the indicator chassis.

PROJECTOR-HYDROPHONE

The CP7 projector was a newly designed unit composed of X-cut Rochelle salt crystals with a major lobe of approximately 90 degrees. The Model GA4-1 was designed especially for the new higher operating band. The major lobe was very narrow, only about 8 degrees. Both the projector and hydrophone were mounted on the same shaft.

The control and soundhead cables were brought through the pressure hull to the forward battery room where the stack was located. The rotating unit permitted unlimited training in either direction but the associated slip rings ultimately produced so much noise that they were not tried again during the war (rotation was subsequently limited to a few rotations in either direction).

DATA SHEET—*FM Sonar Model 1, No. 3*

Carrier frequency	60 kc
Frequency sweep	± 8 kc
Receiver	Same as FM sonar Model 1, No. 1
Difference frequency band used	500 to 2,000 c
Number of analyzer channels	20
Bandwidth of analyzer channels	75 c
Distribution of analyzer channels	Linear
Audio output	Composite receiver spectrum
Signal indication	PPI and loudspeaker
Sawtooth-modulated oscillator [SMO]	Same as FM sonar Model 1, No. 1
Sawtooth slope	Down
Range scales	500, 1,000, 2,000 yd
Driver amplifier	Two 8005, push-pull
Operation	Class B
Output	100 watts
Projector	CP7
Hydrophone	GA4-1*
Physical assembly	Three sheet metal boxes 22x20x22 in. Indicator (separate) 9x9x24-in. box
Location	Submarine S-34

* GA4-1 had 8x8-in. X-cut Rochelle salt motor.

4.5.4 FM Sonar Model 1, No. 5 (XQLA X-1)

Modifications

Using the data collected on the S-34 and all previous installations the FM sonar Model 1, No. 5 was completely rebuilt and repackaged specifically for fleet-type submarine installation (Figures 12 and 13).

Cabinet Construction

The repackaging marked a radical departure from previous systems in that the old panel-and-rack type of construction was abandoned in favor of drawer and cabinet. The electronic stack consisted of three cabinets containing the five major components: driver amplifier, analyzers 1 and 2, frequency-modulated oscillator, and receiver. These could be mounted vertically to form a stack or distributed as space consideration demanded.

The cabinets were provided with ventilating louvers and the drawers were locked into position by means of thumbscrews (which also served as jackscrews to remove the chassis). Safety latches were provided on the drawer slides. Electrical connection between chassis and cabinet was provided by Cannon plugs aligned by guide pins at the back of each drawer. Provision was made to operate any

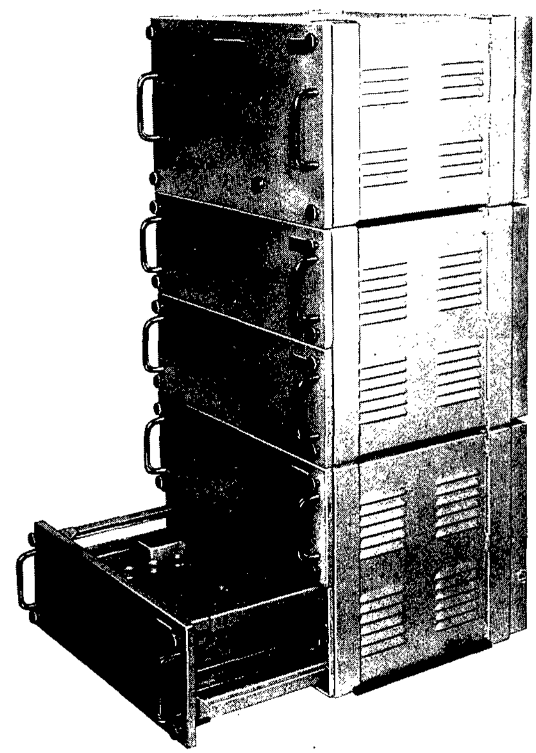


FIGURE 12. FM sonar Model 1, No. 5 (XQLA X-1) electronic stack (oblique view) (Submarine *Spadefish* installation).

chassis removed from its cabinet by means of patch cords. The chassis could be inverted and replaced part way in drawers to simplify testing and repair.

FMO

The distinguishing feature of the frequency-modulated oscillator was the new type of synchronized blanking employed. The controlled

operation of two thyratrons, one associated with the sawtooth generator and the other with the push-pull blanker amplifier circuit, caused blanking at flyback and regulated recycle time. The cathode of this latter tube, the blanker thyratron, was connected to the d-c sawtooth generator by means of a cathode follower while the grid was held constant. As the sawtooth potential was decreased the cathode was carried down toward its grid until the critical bias was reached, the tube fired and the negative pulse on the plate was carried through an *RC* network to the grid returns of the blanker amplifier. The sudden cutoff of the amplifier produced a positive pulse in its plate circuit which was coupled back to the grid of the sawtooth generator thyratron through a second delay network. When this grid became positive this thyratron fired and the sawtooth recycled. Recycling the sawtooth extinguished the blanker thyratron and the circuit was ready for the next cycle.

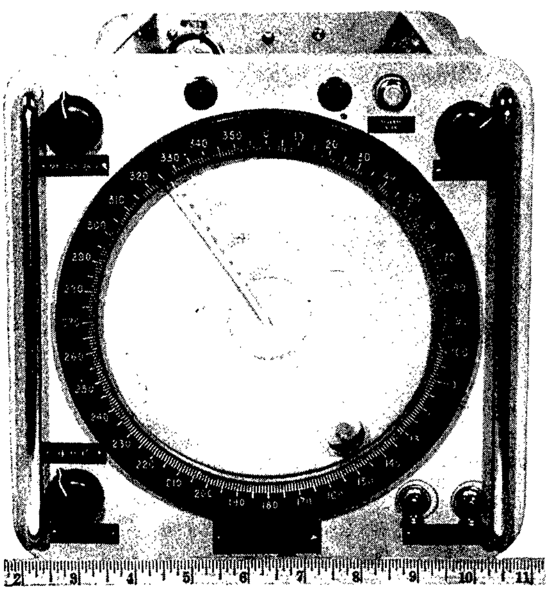


FIGURE 13. FM sonar Model 1, No. 5 (XQLA X-1) indicator unit (front view) (Submarine *Spadefish* installation).

PROJECTOR-HYDROPHONE

The CP10Z-3, an ammonium dihydrogen phosphate [ADP] crystal motor, was housed in a cylindrical case 12 in. long and 11 in. in diameter. The vertical angle of the projected sound beam was approximately 12 degrees wide while the horizontal angle was 90 degrees at 42 kc. A 360-degree rotation was provided.

The GA2-7 hydrophone was 12 degrees wide between the 6-db down points at 42 kc.

DATA SHEET—*FM Sonar Model 1, No. 5** *(XQLA X-1)*

Carrier frequency	42 kc
Frequency sweep	6 kc
Receiver	Redesigned (similar to Model 1, No. 3)
Difference frequency band used	500 to 2,000 c
Number of analyzer channels	20
Bandwidth of analyzer channels	75 c
Distribution of analyzer channels	Linear
Audio output	Composite receiver spectrum
Signal indication	Improved PPI, loudspeaker
Sawtooth-modulated oscillator [SMO]	XQLA
Sawtooth slope	Down
Range scales	150 to 600 yd 300 to 1,200 yd 600 to 2,400 yd
Driver amplifier	Two 838, push-pull
Operation	Class B
Output	250 watts
Projector	CP10Z-3, Serial No. 1689†
Hydrophone	GA2-7, Serial No. 1705‡
Physical assembly	Electronic stack (5 chassis) 45x22x19-in. overall Indicator chassis 19x10x10-in. Loudspeaker 7x7x5-in.
Location	Submarine *Spadefish* (fleet type)

* Systems No. 6 through 10 were essentially the same in all major operational details.
† CP10Z-3 had ammonium dihydrogen phosphate crystal motor.
‡ GA2-7 had 8x8-in. Y-cut Rochelle salt motor.

Chapter 5

PRESENT FM SYSTEM (QLA-1)

5.1 GENERAL DESCRIPTION

THIS DESCRIPTION is applicable to the Navy Model QLA-1 Series of FM echo-ranging equipment (Figure 2), which was built by the Electrical Research Products Division of Western Electric Company by arrangement with the University of California, Division of War Research under Contract NObs-2074, Subcontract 12, dated March 1, 1945. It is designed for installation on either submarines or surface vessels.

FIGURE 1. Craft entering channel.

Vessels and their wakes, small objects, sand banks, antisubmarine nets, and in fact any partially or completely submerged objects that are good supersonic reflectors are represented both audibly by a tone of characteristic pitch from a loudspeaker, and visually, by illuminated spots on a cathode-ray oscilloscope screen in their proper position relative to the operating ship (Figures 1 and 3).

It will be noted by reference to Figure 2 that the various units of QLA-1 equipment are divided into three major groups according to their location aboard ship: indicator and loudspeaker may be located near the conning officer's operating position; the stack holding other electronic equipment may be located at some convenient point near the soundhead; and the soundhead itself may be mounted topside (on submarines) or bottomside (on submarines or surface vessels).

5.1.1 Physical Characteristics

QLA sonar echo-ranging equipment is comprised of the following principal units which are shown in Figure 2 in their relative positions on board ship (identifying letters in the listing correspond to those on the diagram):

Frequency-Modulated Oscillator A. This generates alternating electric current at varying (linear sawtooth) supersonic frequency.[a]

Driver B. This is used to amplify the oscillations to a useful level.

Soundhead C. This unit contains a projector and a hydrophone. The projector converts the electrical energy from the driver into sound waves radiated into the water. The hydrophone picks up the returning echoes and converts them back into electrical energy.

Hoist-Train Mechanism D. This mechanism is used for raising and lowering the soundhead and for rotating it at the rate and through the angle desired.

Receiver E. The receiver mixes returning echoes with a sample of the projected sound and amplifies the resulting signal.

Analyzer F. This unit channels the difference

[a] FMO frequency in QLA-1 covers the band from 46⅔ to 36 kc, rather than 48 to 36 kc, to accommodate the system to production transducers in which the frequency response at the upper end tended to fall off. They were relatively flat between 36 and 46⅔ kc, . . . hence the change.

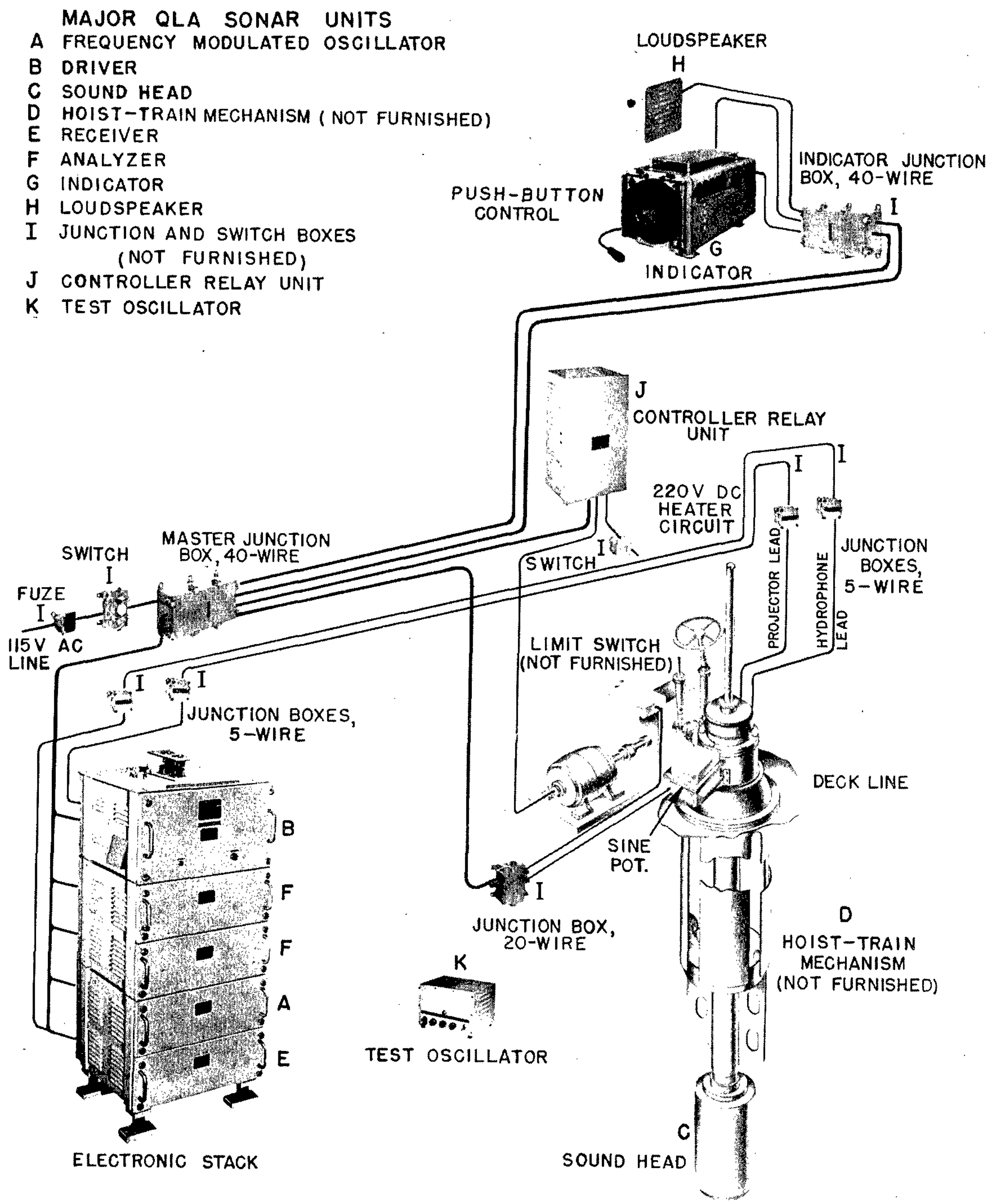


FIGURE 2. QLA-1 units grouped according to shipboard position.

frequencies and by means of a rapid-scanning electronic switch passes them in correct time sequence to the intensity amplifier of the cathode-ray oscilloscope in the indicator.

Loudspeaker H. This unit converts frequency differences into sounds.

Junction Boxes I. Through these units the various units are interconnected.

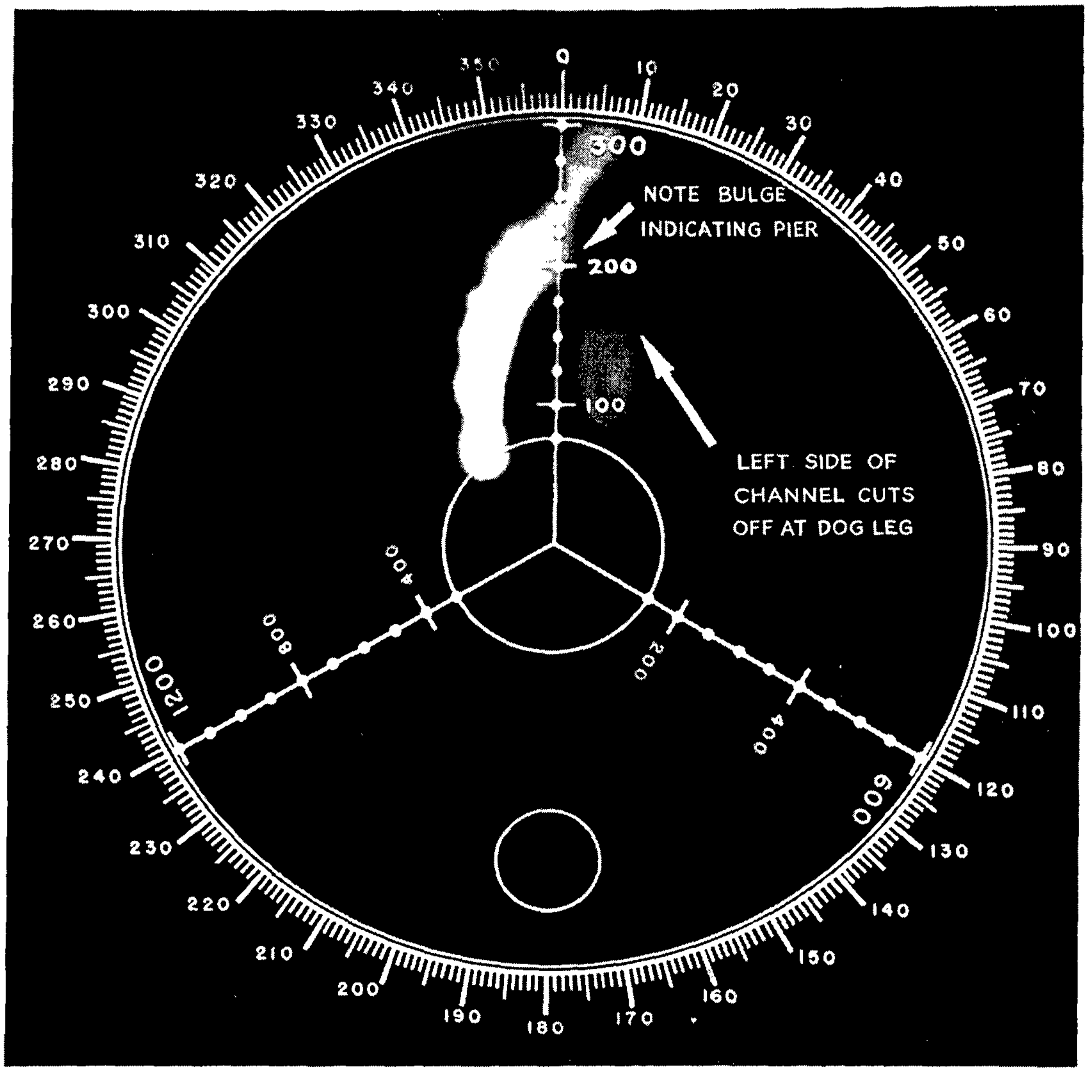


FIGURE 3. QLA-1 view of channel as seen on indicator of installation aboard craft shown in Figure 2.

Indicator G. The indicator contains a cathode-ray tube on whose face appear spots of light representing echo-reflecting objects in their proper position relative to the operating vessel. All operating controls are located on the indicator box.

Controller Relay Unit J. Soundhead training is controlled through this.

Test Oscillator K. The oscillator is used in setting the end frequencies of the frequency-modulated oscillator.

Miscellaneous. Circuits of each of the individ-

ual chassis are described and diagramed and the principal units illustrated in Section 5.1.2.

Cables are standard Navy types, terminating at the chassis in Cannon DP plugs and at the junction boxes in barrier strips. The chassis are mounted in drawers which may be pulled out for servicing. Removing the chassis from its compartment breaks all electric connections to it; patch cables and plugs are provided for operating a chassis when it is removed for servicing.

Bulk data are given in Table 1 which presents both the crated and uncrated weights and volumes of the equipment supplied.

Tube data descriptive of the vacuum-tube complement of each unit including the test oscillator are given in Table 2.

TABLE 1. Equipment supplied.

Quantity per equipment	Name of unit	Navy type designation	Overall dimension A. Crated B. Uncrated Height width depth (in.)	Volume A. Crated B. Uncrated (cu ft)	Weight A. Crated B. Uncrated (lb)
1	Indicator cabinet	CW-55190	A. 12½ x 13 x 27	A. 2.54	A. 48
			B. 10¾ x 10⅞ x 24	B. 1.62	B. 32
1	Cabinet assembly consisting of:	CW-43070			
1	Driver cabinet		A. 18½ x 27½ x 21	A. 6.18	A. 150
			B. 13 x 22 x 19⅜	B. 3.21	B. 73
1	Analyzer cabinet		A. 18½ x 25½ x 21	A. 5.73	A. 100
			B. 17 x 22 x 19⅜	B. 4.19	B. 69
1	FMO-Rec. cabinet		A. 21½ x 27 x 23½	A. 7.89	A. 143
			B. 17 x 22 x 19⅜	B. 4.19	B. 100
1	Driver chassis	CW-52363	A. 14½ x 25½ x 20½	A. 4.39	A. 215
			B. 13 x 22 x 19	B. 3.14	B. 185½
1	Anal. No. 1 chassis	CW-53334	A. 9½ x 25½ x 21½	A. 3.01	A. 125
			B. 8⅜ x 21⅞ x 19⅝	B. 2.08	B. 99
1	Anal. No. 2 chassis	CW-53335	A. 9½ x 25½ x 21½	A. 3.01	A. 115
			B. 8⅜ x 21⅞ x 19⅝	B. 2.08	B. 95
1	FMO chassis	CW-35108	A. 9½ x 25½ x 21½	A. 3.01	A. 90
			B. 8⅜ x 21⅞ x 19⅝	B. 2.08	B. 66½
1	Receiver chassis	CW-46282	A. 9½ x 25½ x 21½	A. 3.01	A. 125
			B. 8⅜ x 21⅞ x 19⅝	B. 2.08	B. 101
1	Indicator chassis	CW-55190	A. 11 x 11½ x 26½	A. 1.94	A. 70
			B. 9½ x 10¼ x 22⅝	B. 1.28	B. 52
1	No. 1 spares box	QLA-1	A. 10½ x 15½ x 30	A. 2.83	A. 80
					B. 60
1	No. 2 spares box	QLA-1	A. 10½ x 15½ x 30	A. 2.83	A. 160
					B. 140
1	CRO tube	7BP7	A. 12 x 12 x 22	A. 1.83	A. 18
			B. 7 diam x 13¾	B. 0.31	B. 5
1	Controller relay unit	GCH-29753	A. 29½ x 16 x 11	A. 3.00	A. 70
			B. 21 x 12 x 8½	B. 1.24	B. 56½
1	Soundhead	CJJ-78256	A. 36 x 22 x 19½	A. 8.94	A. 550
	Incl. cables		B. 30½ x 14½ diam	B. 2.91	B. 460
1	Test oscillator	GCH-60148	B. 7¼ x 10½ x 8¼	B. 0.36	B. 15
1	Loudspeaker	CW-491126	B. 8 x 8 x 6¼	B. 0.23	B. 10
	Test cables				
3	Test patch cord (stack)				
1	Test patch cord (indic.)		B. 6 x 11 x 12	B. 0.46	B. 10
1	Remote control cable and pushbutton				
			TOTAL	A. 60.14	B. 2059
				B. 31.46	B. 1629½

5.1.2 Operating Characteristics

Figure 4 is a functional diagram of QLA-1 sonar.

TABLE 2. Electronic tube complement.

Unit	Designation	Type	Function
FM Oscillator unit	V101	5R4-GY	Rectifier
	V102	6L6-GA	Voltage regulator
	V103	6J5-GT/G	Reg. pwr. supply buffer
	V104	6SJ7-GT	Regulator control
	V105	2050	Sawtooth generator
	V106	6SJ7-GT	Constant current
	V107	2050	Pulse generator
	V108 (A&B)	6SN7-GT	(A) Sawtooth gen. buffer (B) Pulse gen. buffer
	V109, V110	6J5-GT/G	Multivibrator
	V111	6J5-GT/G	Multivibrator buffer
	V112	6SN7-GT	Blanker amp.
	V113	OD3/VR150	Voltage regulator
Driver unit	V201, V202	6L6-GA*	Voltage amplifiers
	V203, V204	838	Driver amplifiers
	V205, V206	866-A/866	H.V. rectifier
	V207	5R4-GY	L.V. rectifier
Receiver unit	V301	6SJ7-GT	Voltage amplifier
	V302, V303	6SK7-GT	Voltage amplifiers
	V304	6SN7-GT	Voltage amplifier
	V305	6V6-GT/G	Power amplifier
	V306	5R4-GY	Rectifier
	V307	6L6-GA	Voltage regulator
	V308	6SJ7-GT	Regulator control
	V309	OD3/VR150	Voltage regulator
Analyzer No. 1	V401 (A&B)-V405 (A&B)	6SN7-GT	Detectors
	V406-V415	6SN7-GT	Switches
	V416	5Y3-GT/G	Rectifier
Analyzer No. 2	V601 (A&B)-V605 (A&B)	6SN7-GT	Detectors
	V606-V615	6SN7-GT	Switches
	V616	6J5-GT/G	Line-matching amp.
Indicator unit	V801	6SN7-GT	Pulse generator
	V802	2X2/879	H.V. rectifier
	V803	6SN7-GT	Synch. pulse amp. and limiter
	V804, V805	6H6-GT/G	Rad. sweep gen. h. and v.
	V806, V807	6L6-GA	Deflection coil drivers, horizontal
	V808, V809	6L6-GA	Deflection coil drivers, vertical
	V810	7BP7	PPI
	V811	6SN7-GT	Intensity amplifier and limiter
Controller relay unit	V901	5V4-G	Rectifier
	V902, V903	2050	Thyratrons
Test oscillator	V101, V102	6SN7-GT/G	Oscillators
	V103	5Y3-GT/G	Rectifier

* Or 6B4G tubes.

All the electronic equipment associated with the QLA sonar gear operates on 110- to 125-v, 60-c, single-phase, alternating current. Table 3 lists the heat dissipation of each major unit together with the current requirements for starting standby and normal operation. The power factor of each section of the equipment is also listed in Table 3.

IMPEDANCE DATA

The output of the driver is 250 watts into a 250-ohm resistive load. The output of the re-

ceiver is ½ watt into the 50-ohm resistive load of the analyzer. The output impedance to the loudspeaker is 6 ohms. The complex impedance of each section of the soundhead as a function of frequency appears on the plots Figure 5.

Receiver Data

The QLA sonar receiver, which is a heterodyne type, mixes the echo with the signal being transmitted and produces a beat frequency equal to the difference in frequency between them. See Figure 6.

The difference frequency produced by mixing the signal and echo may have any value between 0 and 10⅔ kc, but only the 500- to 2,000-c band is used. This is divided into 20 channels by a frequency analyzer for presentation on the indicator screen. See Figure 4.

For each of the 20 channels (band-pass filters) there is a corresponding radius on the circular CRO screen such that a spot on the screen is brightened at a position whose distance from the center is proportional to the frequency of the filter being excited, and hence proportional to range.

The bearing or radial direction at which a spot appears on the screen depends upon the bearing of the hydrophone when receiving the corresponding reflected echo. A network which includes a sine potentiometer coupled to the hydrophone column and the cathode-ray sweep generator orients the trace on the screen so

TABLE 3. Power distribution of QLA sonar system.

Equipment	Condition	Volts line	Watts		Amperes		Power dissipated	Power factor
			Surge	Steady	Surge	Steady		
Total	Master power on; amplifier power on; gain up	116	1398	1351	13.2	13.2	1101	0.87
	Master power on; amplifier power on; gain down	116	1068	1036	10	10	...	0.86
	Master power on; amplifier power off	116	755	755	7	7	...	0.93
Analyzer No. 1	Normal	116	91	79	0.85	0.7	79	0.86
Analyzer No. 2	Normal	116	91	70	0.75	0.6	70	0.84
Driver	Master power on; amplifier power off	116	220	200	1.8	1.75	200	0.96
	Master power on; amplifier power on; gain off	116	515	510	4.65	4.65	510	0.95
	Master power on; amplifier power on; gain on	116	838	828	8.1	8.1	578	0.88
Receiver	Normal	116	50	215	...	2.12	135	0.87
FMO	Normal	116	60	100	0.6	0.97	100	0.91
Indicator	Master power on; amplifier power off	116	75	65	0.7	0.66	145	0.86
	Master power on; amplifier power on	116	76	71	...	...	...	...

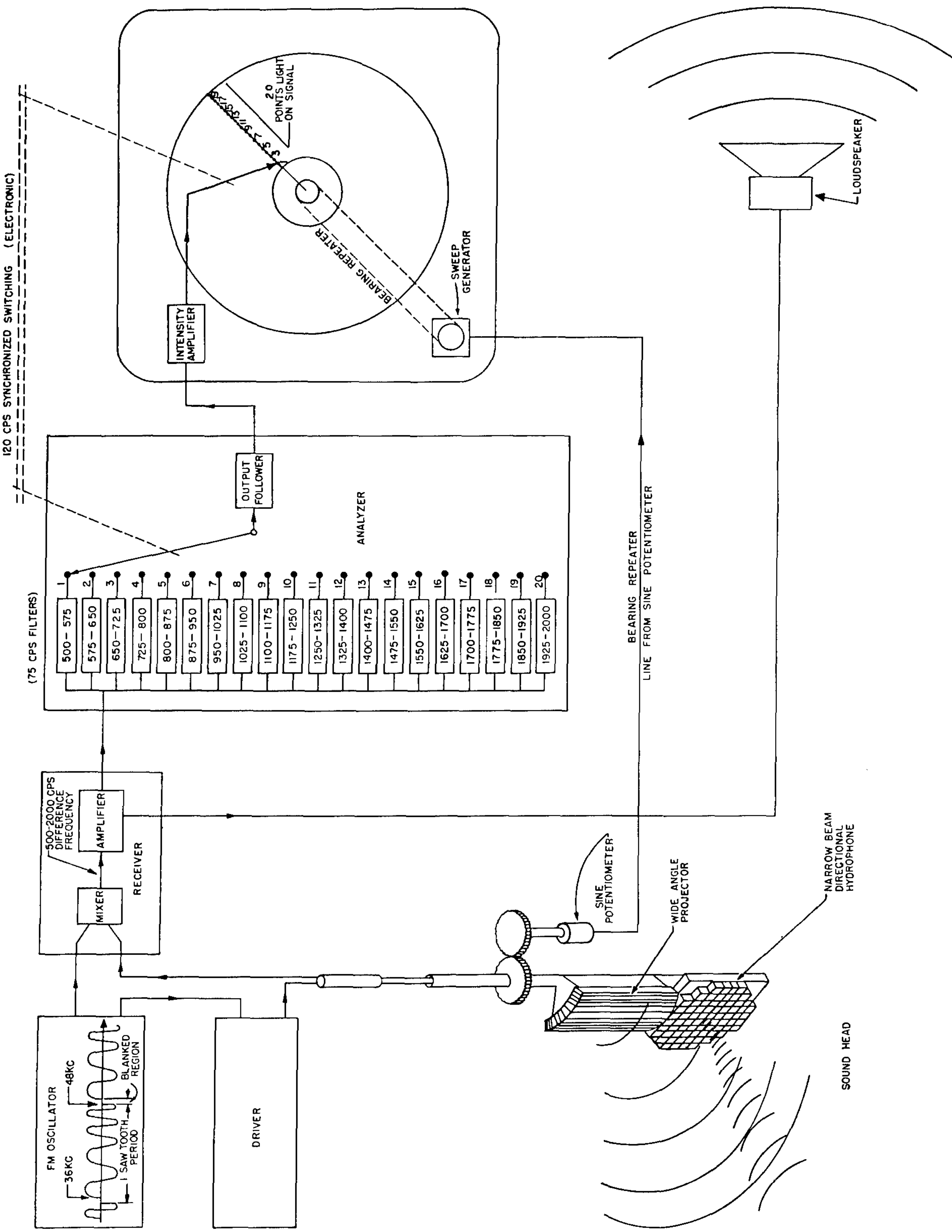


FIGURE 4. QLA-1 simplified functional diagram.

that it is at the same angle with respect to the center line of the screen that the hydrophone bearing is with respect to the center line

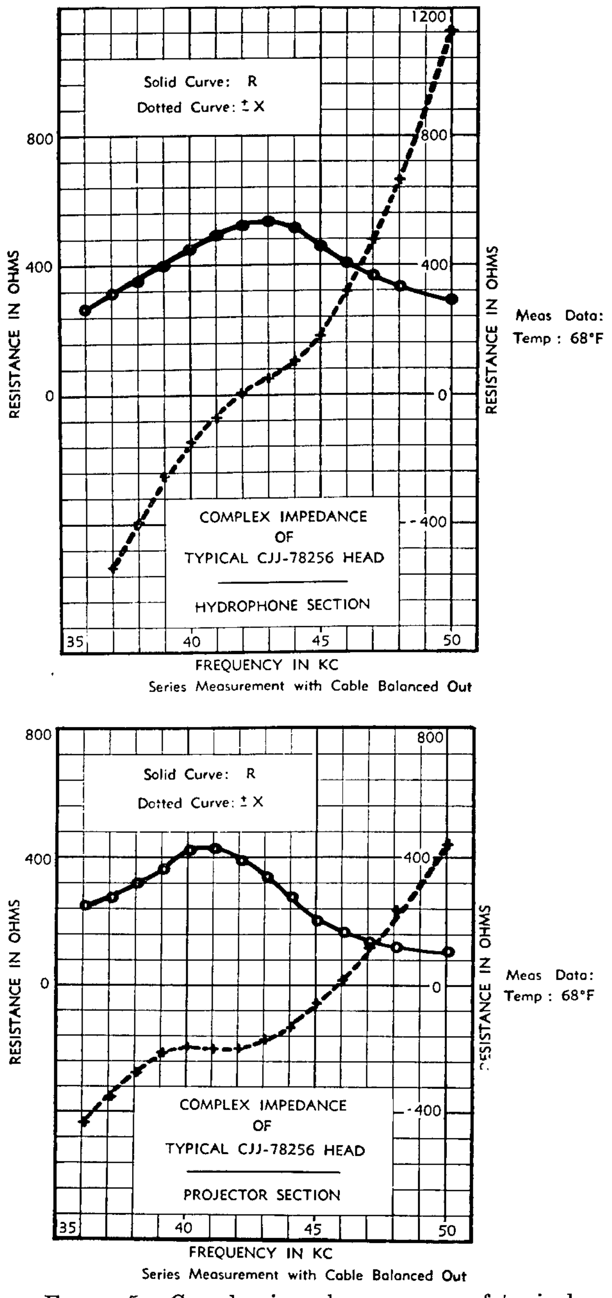


FIGURE 5. Complex impedance curves of typical CJJ-78256 soundhead.

of the ship. The screen thus indicates the relative bearing of the echo.

It is evident that if there are several objects that produce echoes each is represented by a corresponding difference frequency; if there are several objects at the same bearing, as many difference frequencies appear simultaneously. See Figure 7.

FREQUENCY DATA

The operating frequency band of QLA-1 extends from 46⅔ to 36 kc as diagramed in Figure 8. This sawtooth-swept frequency is generated by a voltage-sensitive multivibrator controlled by a sawtooth generator. The regulated power supply for the FMO contains less than 5 mv of 120-c ripple in 300 v at 80-ma output. The supply is so stabilized that 5 per cent variation in line voltage produces less than ¼ per cent variation in the rectified d-c voltage. A tabulation of range scales versus the corresponding sawtooth period follows:

Range scale	Range Minimum	Range Maximum	Period (± ½%)
300 ft	75 ft	300 ft	0.67 sec
300 yd	75 yd	300 yd	2.00 sec
600 yd	150 yd	600 yd	4.00 sec
1,200 yd	300 yd	1,200 yd	8.00 sec
3,000 yd	750 yd	3,000 yd	20.00 sec

SELECTION OF RANGE SCALES

Change in the range comprehension of the system is accomplished by varying the rate at which frequency changes with time. An echo from a target at 300 yd, for example, produces the same difference frequency (when heterodyned with the outgoing signal) as does the echo from a target at 3,000 yd *providing that the range-scale setting is properly adjusted* for a maximum of 300 yd in the first instance, and for a maximum of 3,000 yd in the second. This makes it possible to bring all targets (within the ultimate range of the system) into the comprehension of the analyzer by making appropriate adjustments in the range-scale setting.

RANGE AND BEARING DEFINITION

Range definition is limited by the resolving power of the frequency analyzer to about three per cent of the maximum range. The accuracy with which range can be determined is further limited by the doppler effect (Chapters 2 and 8). The directivity of the receiving hydrophone limits bearing resolution to roughly

three degrees although the bearing can be read visually to about one degree by taking the center bearing of the indication.

Directivity Characteristics

In the QLA sonar equipment the soundhead constitutes the radiating system. Figure 9 is a plan view of the directivity patterns formed by the hydrophone and projector section. Figure 10 represents graphically the field response of the two sections measured with standard hydrophones and projectors. Frequency is graphed versus the response in decibels from the indicated arbitrary standard.

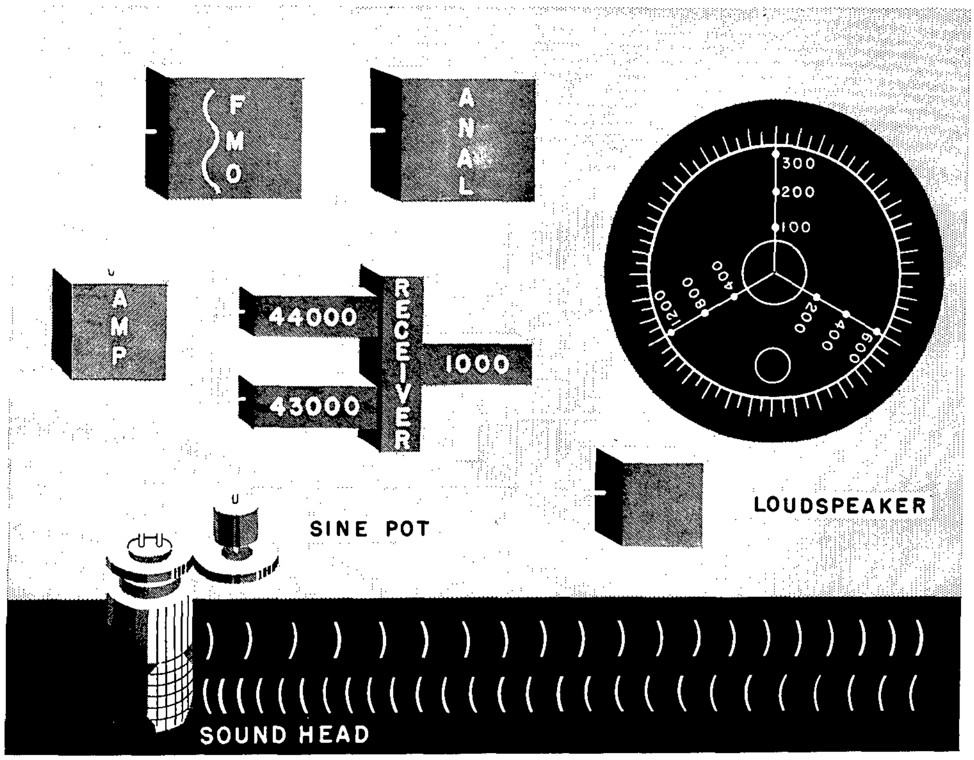


Figure 6. Block diagram of QLA-1.

Maximum Scanning Rate

The maximum angular rate of speed at which QLA sonar can scan depends upon the maximum range for which the equipment is being operated (Figure 11).

The projector transmits sound into the water over an 80-degree arc, or 40 degrees either side of the hydrophone. Thus a particular target is in the field of the projector for about 40 degrees of its rotation before it is observed by the receiver. The rotation of the soundhead must be such that the soundhead rotates less than 40 degrees in the time the sound takes to travel out to the maximum range and back.

The maximum useful speed of rotation of the soundhead (in revolutions per minute) is approximately 5,000 divided by the range in yards. On short ranges the speed is limited by the characteristics of the mechanical system to about 10 rpm. In a particular installation the choice of speeds is dictated by the service intended. The scanning speed at long ranges can be increased if the search sector is limited to about 50 degrees; the whole area can then be covered by a series of sector-scanning operations.

Doppler Effect

All FM systems determine range as a function of the frequency of the echo. The doppler effect, of course, results in a shift in the fre-

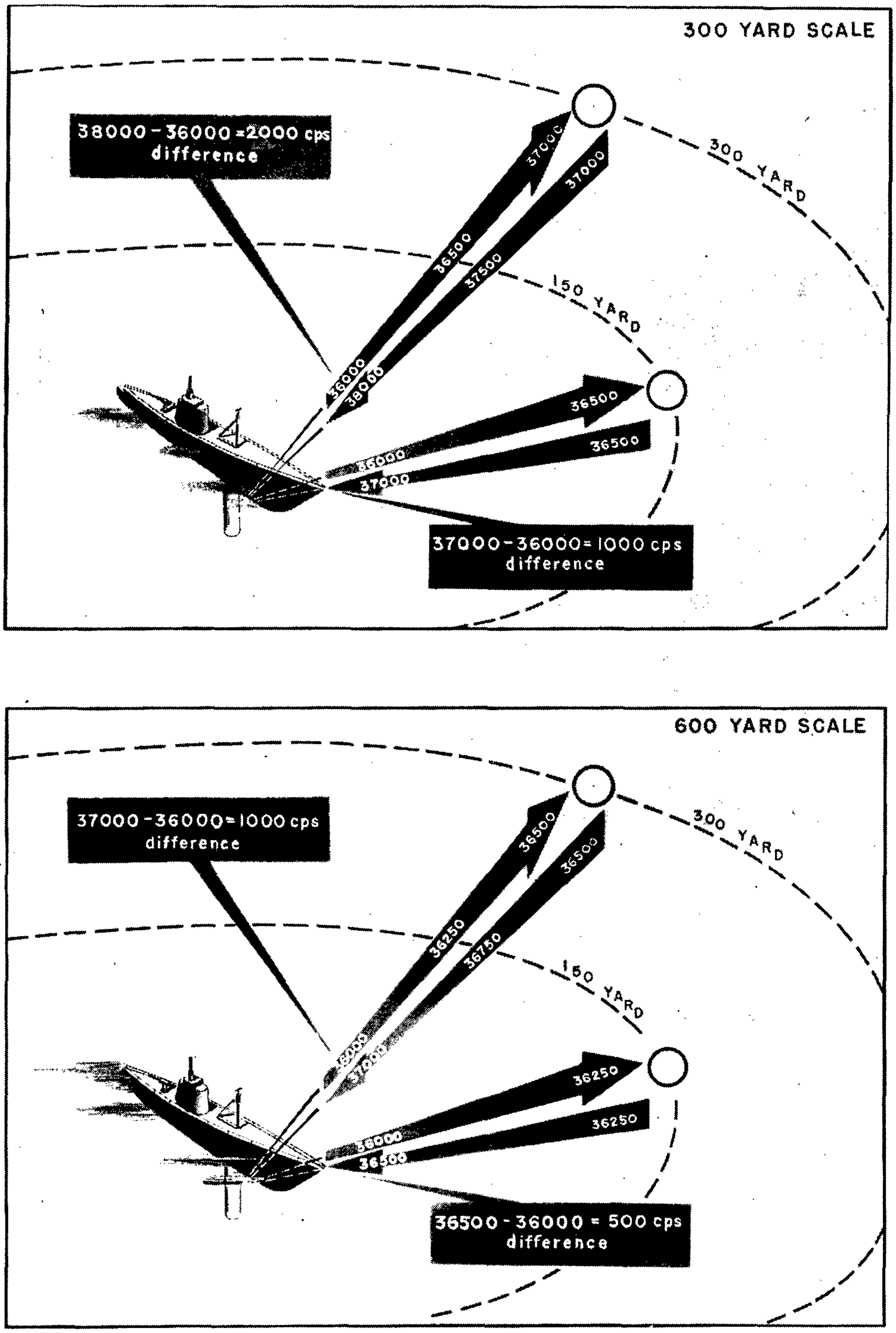


FIGURE 7. Range scales vs difference frequency.

quency of the echo. In QLA-1 the magnitude of this doppler shift is 75 c, or one channel in the analyzer for each $2\frac{1}{2}$ knots of relative range rate. The apparent range is greater than the true range when closing on a target, and is smaller than the true range when the distance to the target is opening. For detailed discussion of this effect and means of turning it to advantage see Chapters 2, 4, and 8.

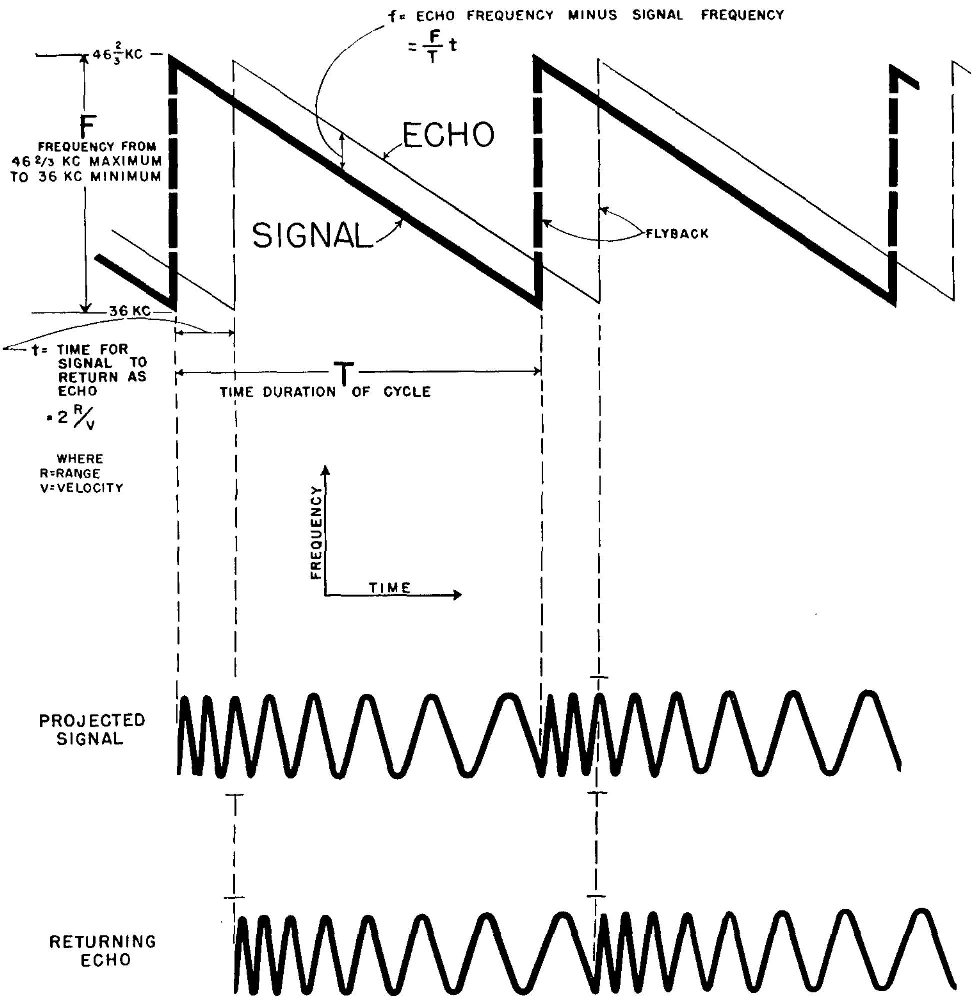


FIGURE 8. Graphic representation of frequency vs time.

5.2 FUNCTIONAL DESCRIPTION

5.2.1 General

Figure 12 is a block diagram of the various components comprising a QLA system. The electronic equipment consists of a five-chassis stack, an indicator, and a loudspeaker, each in its own cabinet. In addition to the electronic equipment, there is the soundhead and its associated hoist-train mechanism.

Two views of the electronic stack are shown in Figure 13 with the positions of the five chassis as indicated in Figure 2. The indicator and loudspeaker are pictured in Figure 2. The function of each of the chassis is indicated in the block diagram (Figure 12) and described in detail in the following text.

The QLA soundhead may be mounted either topside (submarines) or bottomside (submarines or surface vessels) on standard columns. The training of the QLA soundhead is arranged for either a narrow-sector scan or a wide scan

of about three revolutions before automatic reversal, with reversal possible at any point at the option of the operator. The soundhead scanning controls are described under appropriate heading near the end of this section.

and blanking circuits, and a voltage-sensitive oscillator.

Tubes V101 to 104 and V113 are in the regulated power supply (Figure 17). Tube V101 is the rectifier. The regulator, a triode-con-

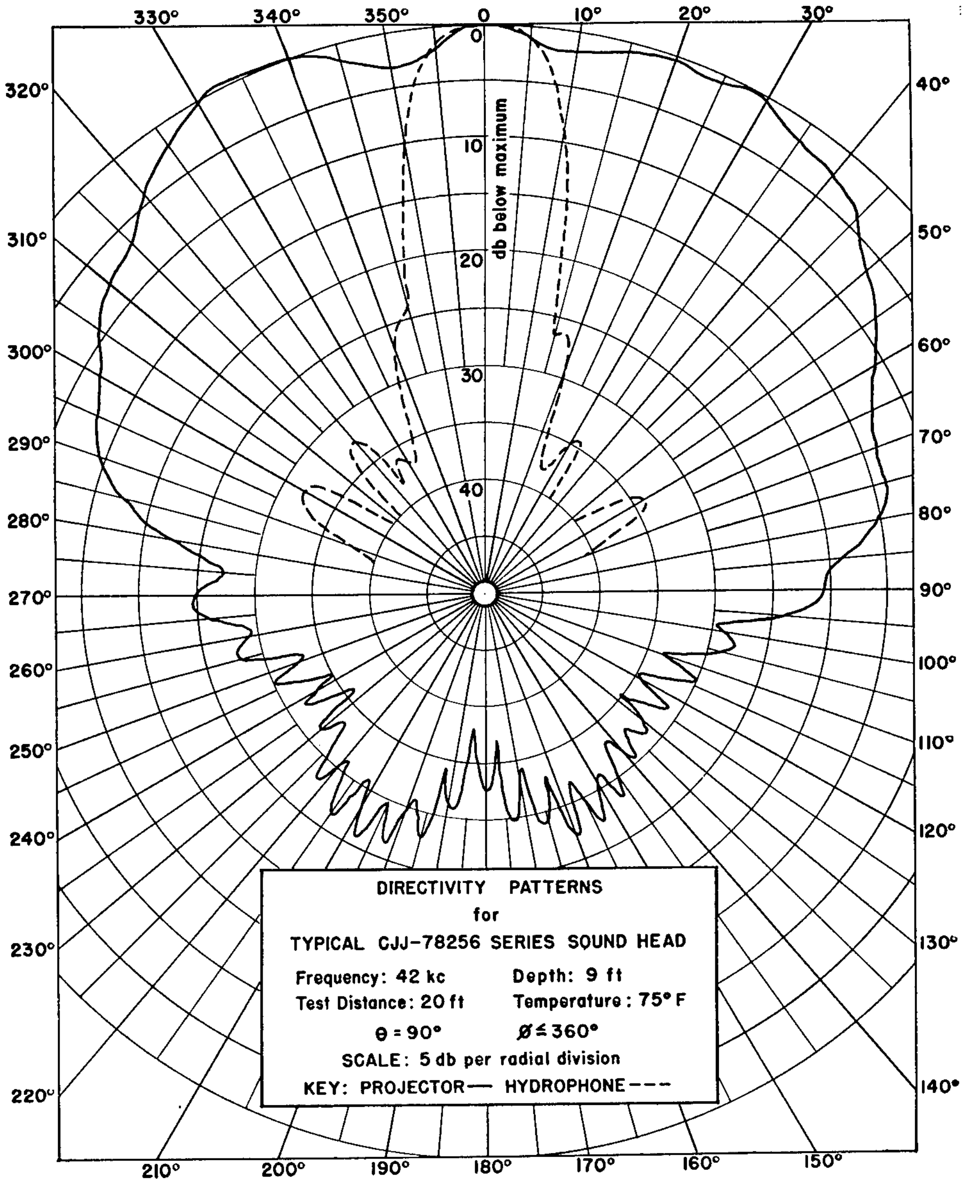
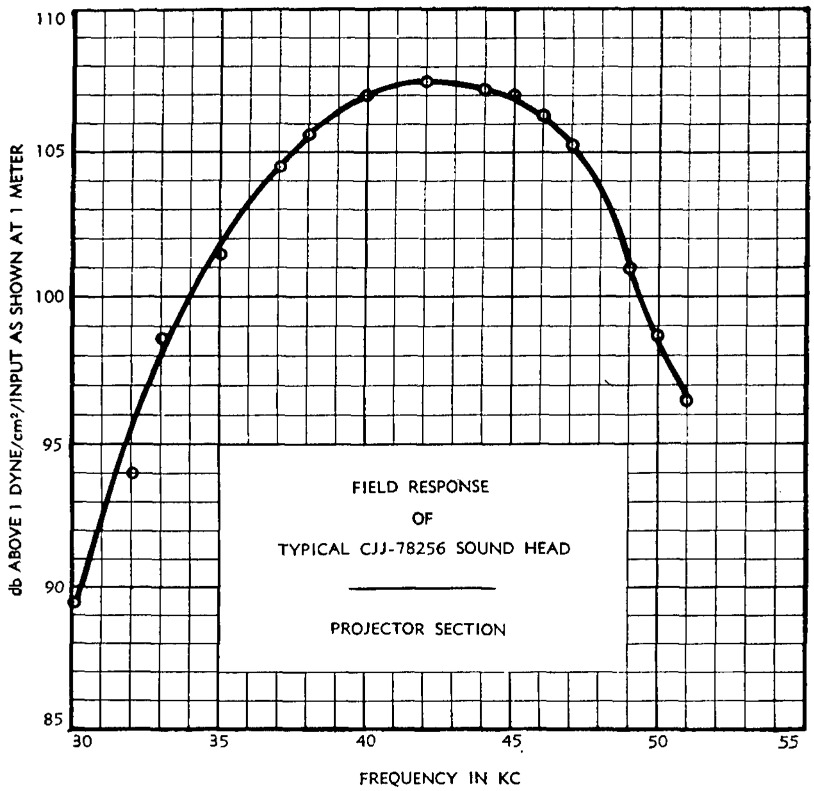


FIGURE 9. Directivity patterns of CJJ-78256 soundhead.

5.2.2 Frequency-Modulated Oscillator

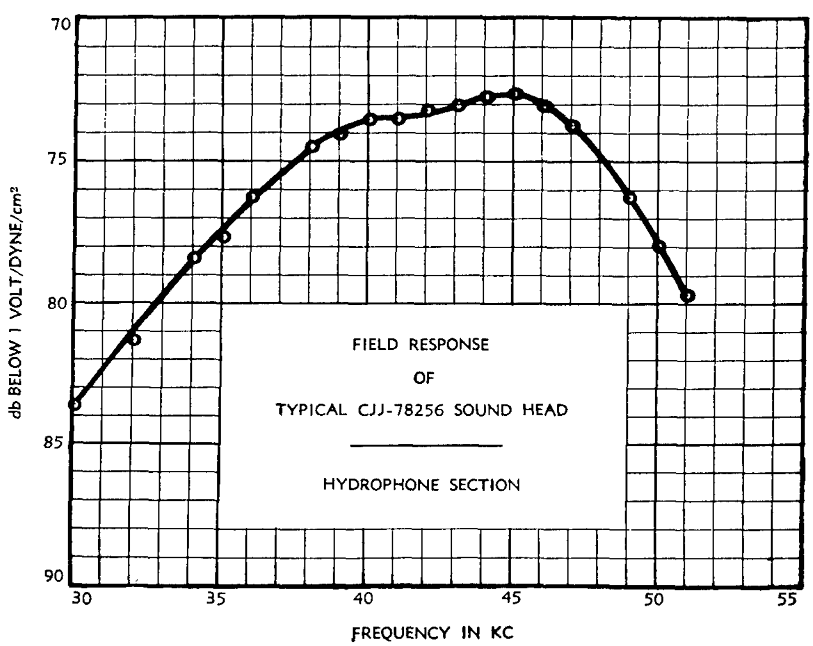
The FM oscillator (Figures 14, 15, and 16) contains a regulated power supply, a linear sawtooth generator with associated triggering

nected pentode V102, is controlled by the pentode voltage amplifier V104 through the cathode follower V103. The grid of V104 connects to a comparatively high positive voltage on a voltage divider so that it receives a substantial part



6.8 Volts Constant Input to the QLA Sonar Amplifier

MEAS DATA:
Std : B-19B
Temp : 75°F
Test Dist : 20 ft
Depth: 9 ft



Voltage Measured across 600-Ohm Load at the End of the Cable

MEAS DATA:
Std : GA2-9
Temp : 75°F
Test Dist : 20 ft
Depth: 9 ft

FIGURE 10. Field response of CJJ-78256 soundhead.

of any voltage variation in the output. The voltage regulator tube V113 then fixes the cathode voltage of the amplifier V104. The condenser C104 couples the output to the grid of discharged by the firing of thyratron V105. The grid of V105 is connected to a tap on the cathode resistor of V108 so that it is kept at a nearly constant voltage with respect to its cath-

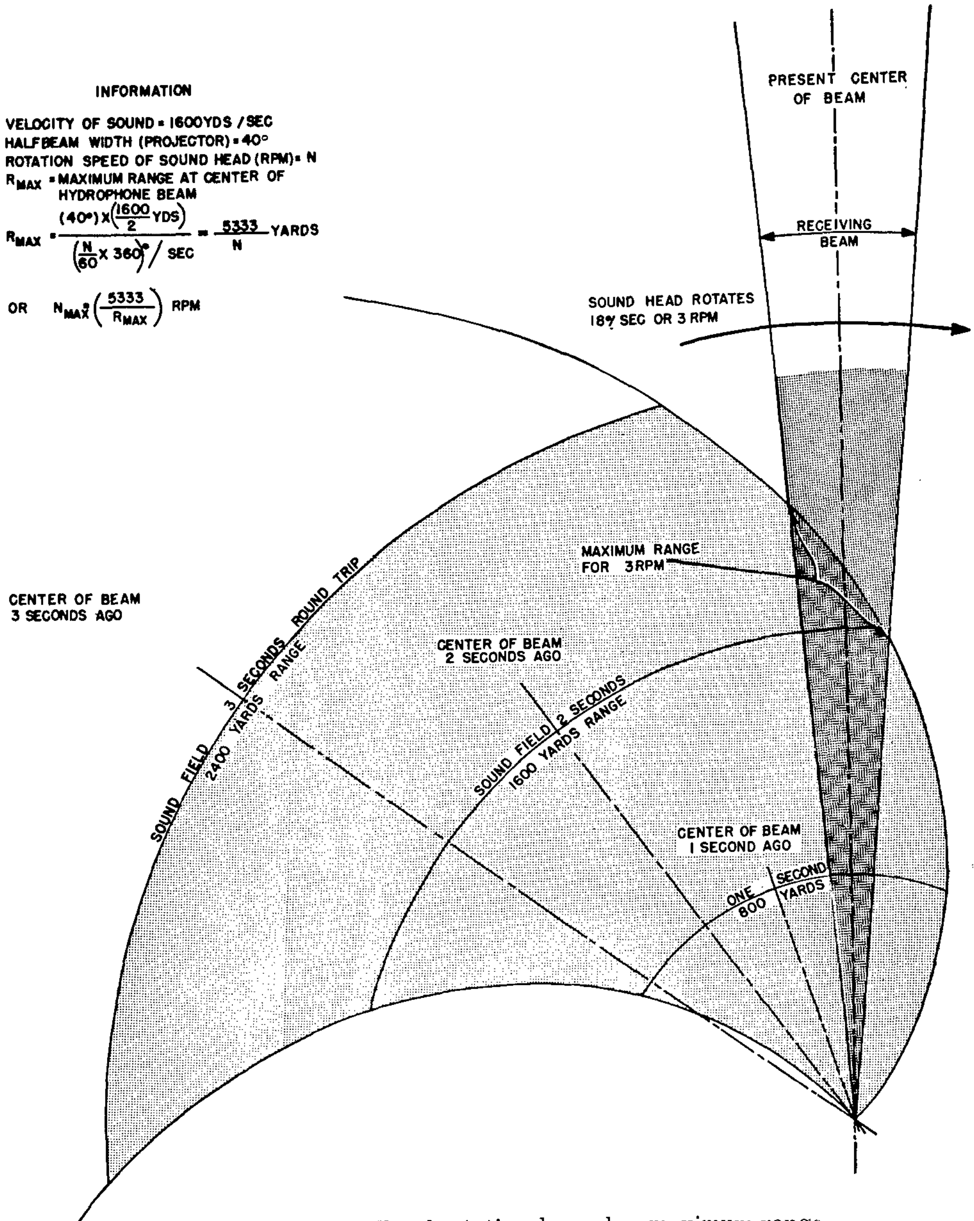


FIGURE 11. Soundhead rotational speed vs maximum range.

V104 reducing any rapid voltage variations to a minimum.

The linear sawtooth generator and blanker circuit (Figure 18) contains a constant-current pentode V106 which charges condenser C106 at a constant rate. The condenser is periodically ode as the cathode voltage changes during the charging cycle of C106. The firing of V105 is initiated by a triggering pulse obtained through a delay network from the pulse-generator thyratron V107 and blanking amplifier V112.

The plate current of tube V106 determines

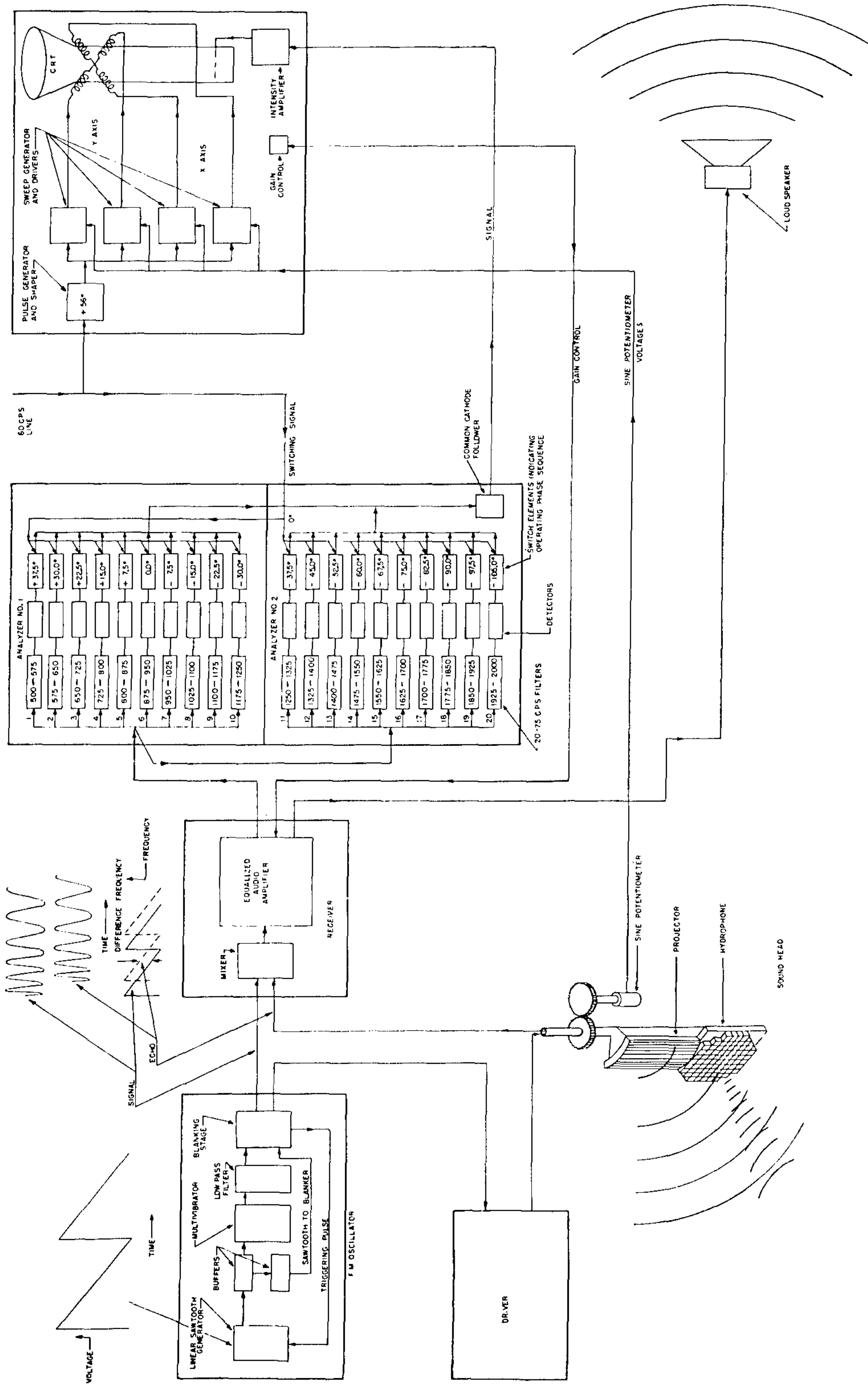


FIGURE 12. Block diagram indicating function of each chassis in QLA-1.

the rate of change of voltage across C106 and therefore the rate of change of frequency and the corresponding range scale. This current is

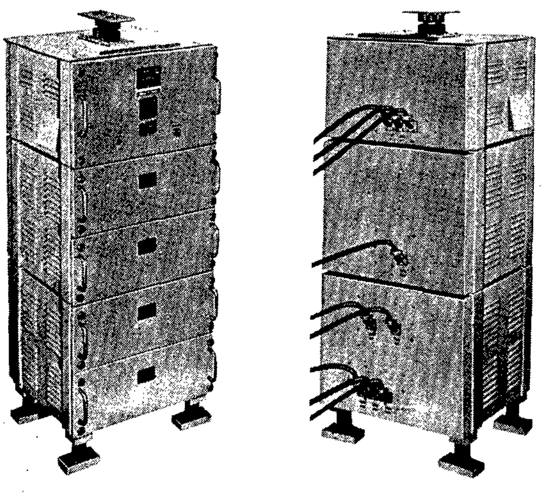


FIGURE 13. Electronic stack, front and back view.

primarily determined by the cathode resistor of V106; one of five values of cathode resistance can be selected to give one of the five available range scales. The lowest resistance R145 to-

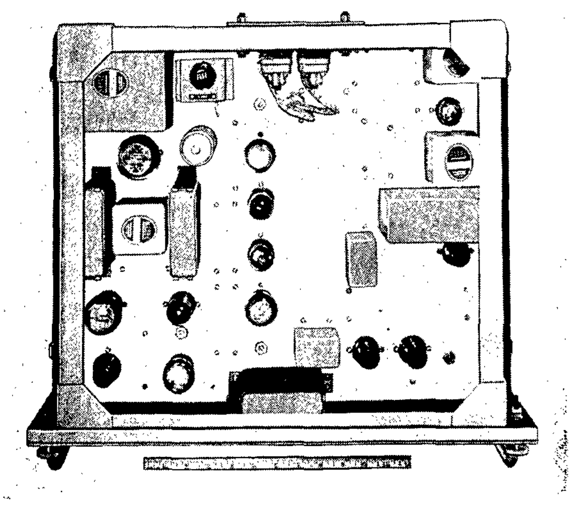


FIGURE 14. FM oscillator, top view.

gether with a cathode decoupling network is found in the FM oscillator; the remaining resistance values are made up by adding to this resistance the desired one of four resistors R849, R850, R851, or R853, found in the indicator. Potentiometer R143 gives a fine adjustment of the rate of charge of the condenser C106 and provides compensation for tube variations.

The sawtooth voltage output obtained from the plate of V106 is repeated by two cathode followers, the two sections of V108, which are introduced to buffer the oscillator from the sawtooth generator and the pulse generator from the oscillator.

As the condenser C106 charges the voltage at the plate of V106 decreases carrying with it

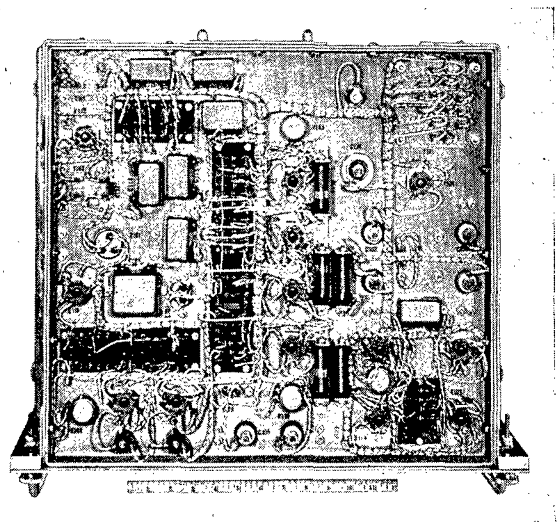


FIGURE 15. FM oscillator, bottom view.

the cathode of V107. When the cathode of V107 is nearly zero with respect to its grid, the tube fires, driving the plate voltage sharply negative. This negative pulse is taken through a delay network consisting of resistor R132 and condenser C114 to the two grids of V112 (C113 is a coupling condenser while resistor R133 is the grid return to ground for V112). This pulse overbiases V112, blanking the output signal (necessary to avoid a disturbance in the receiver at flyback). It also produces a positive pulse at the plate return of V112.

The surge at the plate return of V112 is taken through a second delay network consisting of resistor R111 and condenser C107 (C108 is a coupling condenser) to the grid of V105,

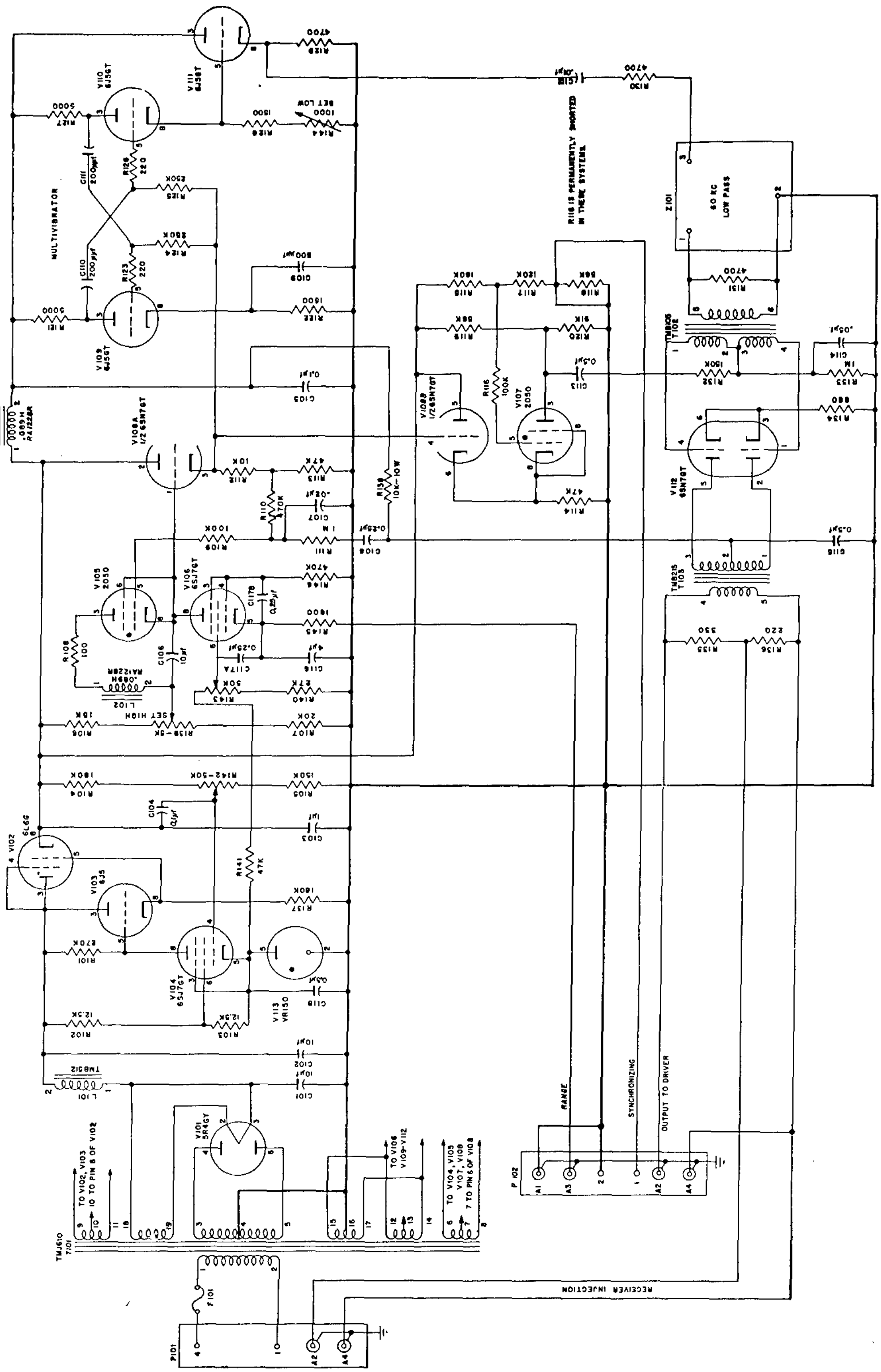


FIGURE 16. FM oscillator, wiring diagram.

triggering it. When V105 fires, the condenser C106 discharges through the inductance L102 and resistor R108. The discharge would be oscillatory except that V105 is extinguished at the first time the current goes through zero. This arrangement produces a rapid discharge and a minimum of lost time in recycling the sawtooth.

The discharging of condenser C106 results in the plate of V106 going sharply positive. The ionization of V107 is extinguished as its cathode, following the plate of V106, goes sharply positive resulting in a reduction of the plate-cathode voltage of V107 below the voltage necessary to sustain ionization. The resulting positive surge in the plate circuit of V107 restores the bias on V112 to its proper operating value and completes the sawtooth cycle.

5.2.3 Auxiliary Recycling Modification

Resistor R118 may be connected to synchronize the flyback with the reversal of rotation of the soundhead (Figure 18). Opening of relay contacts added across R118 raises the grid voltage of the thyratron V107. This resistor is of such value that if the sawtooth has run through more than one-half of its normal cycle, the rise in grid voltage is sufficient to fire V107 and recycle the sawtooth. This operation, a feature of considerable importance at short ranges and narrow sectors, causes the blanked region to lie at the edges of the area being scanned. In the current systems this feature did not seem desirable and R118 is shorted inside the FMO chassis.

A positive-bias multivibrator employing two triodes V109 and V110 (Figure 19) is used in this application as a voltage sensitive oscillator because its frequency is readily controlled by varying the voltage to which the two grids are returned (the junction of R124 and R125). This voltage is obtained from the sawtooth generator as repeated by the cathode follower. The result is an output that varies in frequency in the desired linear sawtooth manner.

The output frequency band of the multivibrator depends upon the circuit constants and upon the voltage by which the grids are driven. In this equipment the low frequency end (36 kc) is set by varying the resistance in the cathode of V110; an increase in this resistance (rheostat R144) results in an increase in frequency. The high-frequency end (46⅔ kc) is adjusted by varying the maximum value of the sawtooth

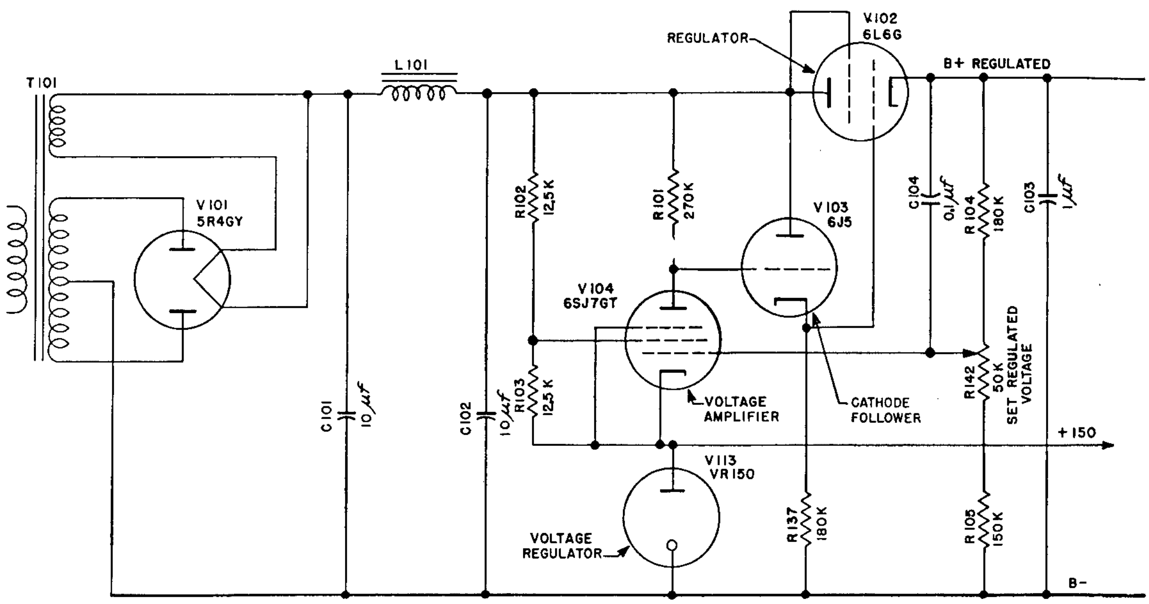


FIGURE 17. Regulated power supply in FM oscillator.

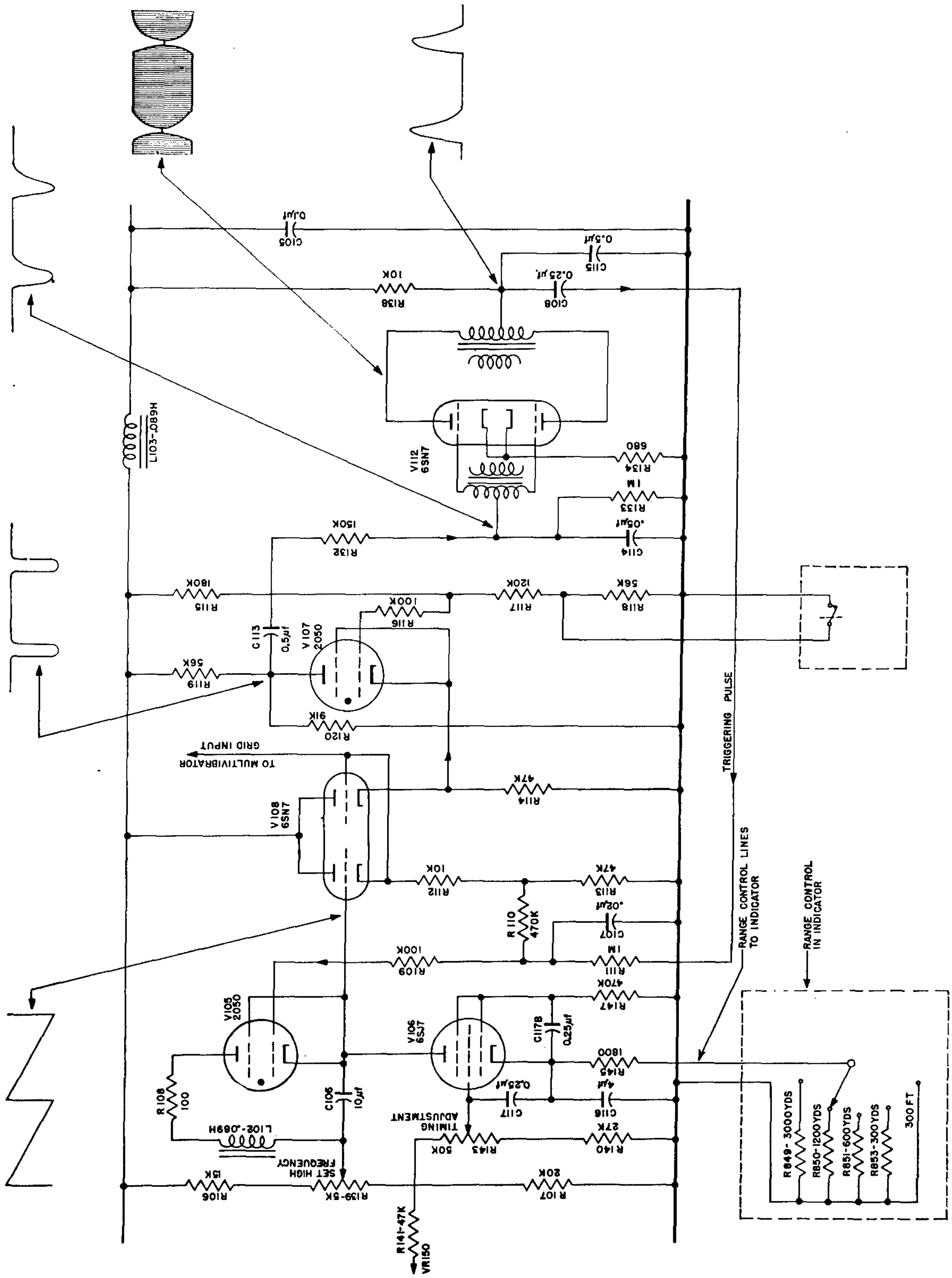


FIGURE 18. FM oscillator schematic: linear sawtooth generator and blanker portions.

voltage received from the sawtooth generator (potentiometer R139, Figure 18).

The output of the multivibrator is taken from the cathode of V110 and is coupled to the low-pass filter Z101 by means of cathode follower V111. The filter is employed because of the large harmonic content in the multivibrator output (largely odd harmonics). The output of the filter is used to drive the two grids of the blanking amplifier V112 (Figure 20).

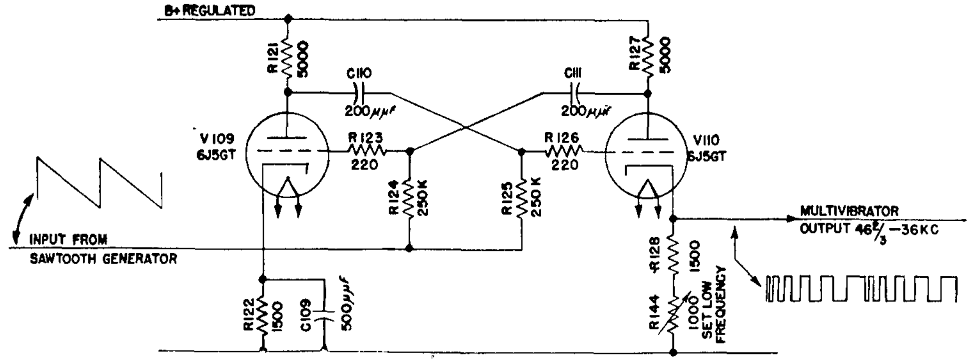


FIGURE 19. FM oscillator schematic: multivibrator portion.

The signal of the FM oscillator chassis is taken from the output of V112. There is no output from the chassis during flyback when V112 is cut off. The blanking pulse applied to the grids of V112 in parallel causes no undesirable disturbance in the push-pull connected output.

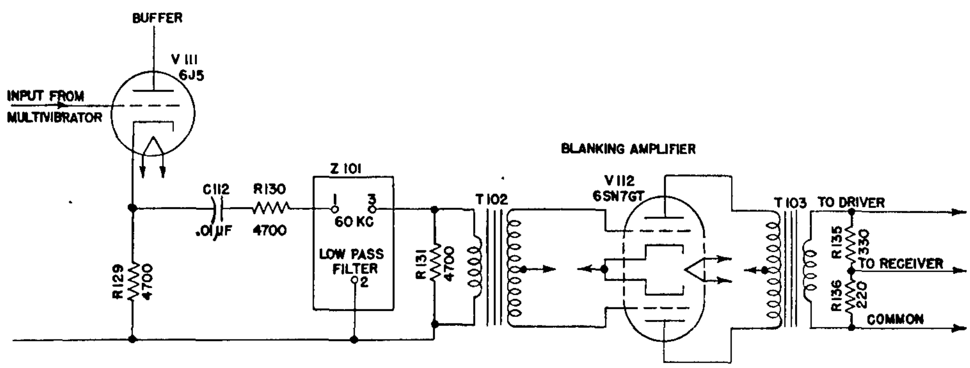


FIGURE 20. FM oscillator schematic: blanking amplifier portion.

The output of the FM oscillator serves a dual purpose: (1) to supply the driver, and (2) to provide heterodyne voltage in the receiver.

5.2.4 Driver

The driver (Figures 21, 22, and 23) has Class B 838 tubes and can supply 250 watts to a resistive load. The 838 tubes are driven by push-pull triode-connected 6L6-GA tubes, operating Class A.

The driver chassis contains two power supplies: the first, a low-voltage supply for the 6L6 (or 6B4) tubes, utilizes a 5R4GY tube; the second has a pair of 866A tubes to supply the 838 tubes.

The driver chassis contains the system-operating relays which are normally actuated by remote control from the indicator. When the master power switch is turned on, relay K202 activates all six chassis with the exception of the plate power in the driver. A time-delay relay K203 operating from the master power relay K202 makes the application of plate power possible after a delay sufficient for heating the filaments.

The amplifier power switch on the indicator operates relay K201 in series with the time delay relay to turn on driver plate power.

Two auxiliary switches S201 and S202, paralleling the master power and amplifier power switches on the indicator, are located on the side

of the chassis. These allow operation of the equipment from the electronic stack when necessary for test. They can be reached through the air vent on the left side of the cabinet.

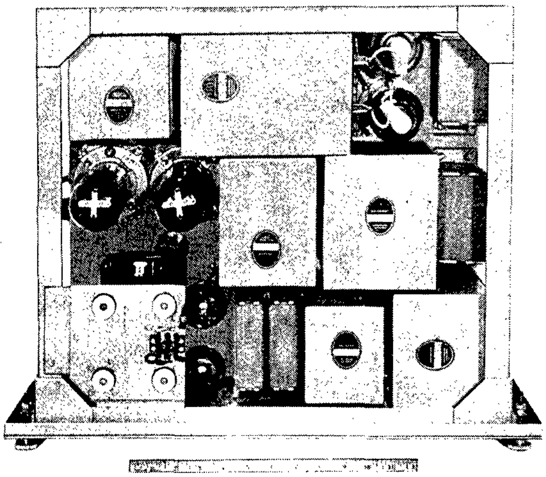


FIGURE 21. Driver unit top view.

The output level may be reduced, if desired, by turning the potentiometer control on the driver panel counterclockwise. It is normally run at maximum.

5.2.5 Receiver

The receiver (Figures 24, 25, and 26) contains a heterodyne detector, equalized amplifier with gain control, and power output stage. The output of the receiver is used to drive both the analyzer and the loudspeaker. Its regulated power supply also supplies the indicator. The first three stages are built on a floating chassis to reduce the effect of external disturbances.

The input circuit of the receiver is shown in Figure 27. The incoming signal from the receiving hydrophone is coupled through a band-pass filter Z301 which reduces interference from water noises whose frequencies lie outside the pass band of the filter. The output of the filter goes to a varistor detector CR301 where it combines with an injection signal from the FM oscillator.

The varistor detector consists of four copper oxide elements. These elements conduct current readily (have low resistance) with the applied voltage in one direction, while they are practically nonconducting (have high resistance) with the applied voltage reversed. The injection from the FM oscillator is much larger than the signal from the hydrophone and thus it determines the polarity across the varistor elements. For one polarity of injection signal the elements *A* and *B* (Figure 27) are conducting, while for the reverse polarity the elements *C* and *D* are conducting. The signal passed from transformer T302 to transformer T303 is thus passed straight through or reversed corresponding to the polarity of the injection. As a result the signal voltage passing to transformer T303 is inverted at the frequency of the injection. The output contains modulation products including the sum and difference of the two input signals.

Both the injection and the input signal from the hydrophone are balanced out of the output. If there were no injection voltage the input signal would be balanced out because as much current would flow through the cross path *C, D* as through the direct path *A, B;* it is apparent

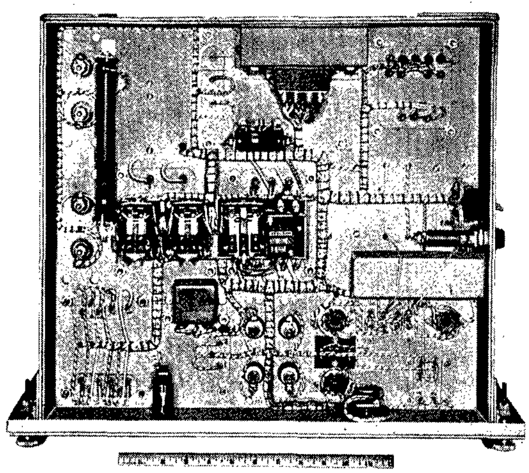


FIGURE 22. Driver unit bottom view.

then that all the input signal that gets across with the aid of injection voltage is modulated by the injection. The potentiometers R302 and R305 are used to provide an accurate means of balancing the injection voltage from the out-

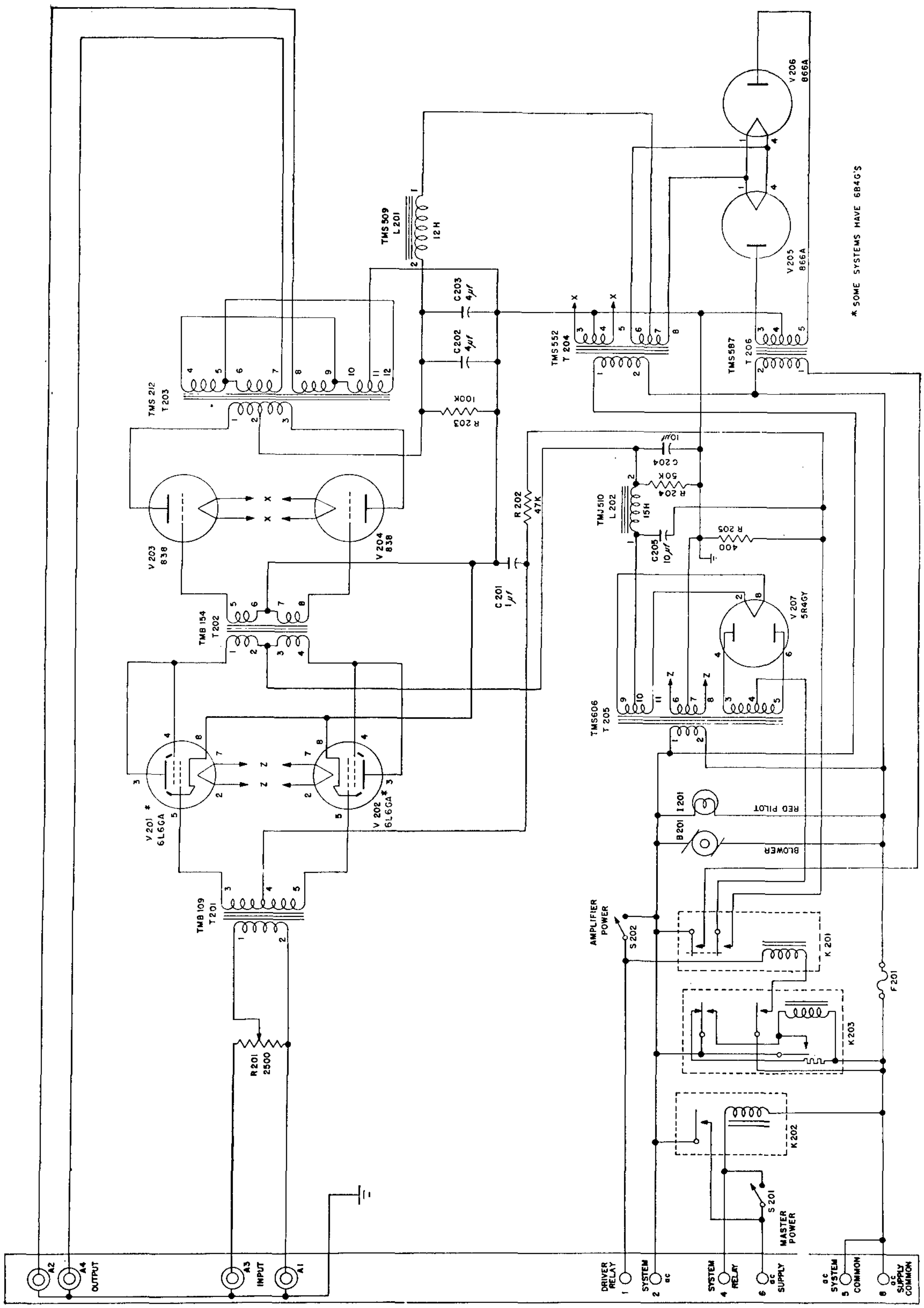


FIGURE 23. Driver unit wiring diagram.

put. This balance eliminates any injection signal from the receiver, which is desirable because the injection signal from the FM oscillator unavoidably contains some low-frequency components which would be passed by the filter Z302. Although these are of very low magnitude they may be large compared with signals received by the hydrophone.

The difference frequency signals developed

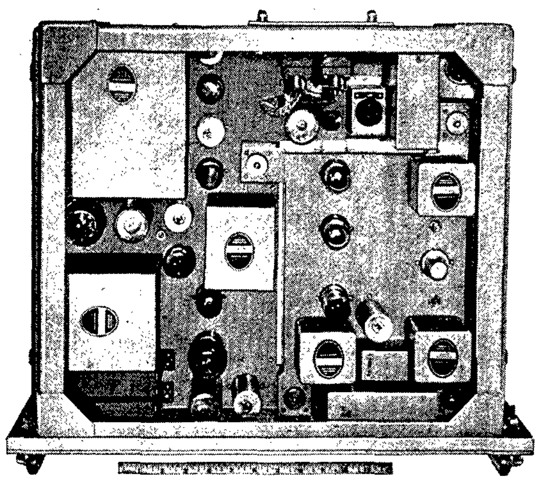


FIGURE 24. Receiver unit top view.

in the varistor are passed through the filter Z302 and transformer T304 to the grid of the first tube V301 (Figure 28). The first amplifier stage has a plate load tuned to 2,400 cycles per second (L301, C306) giving it approximately 24 db more gain at 2,000 cycles per second than it has at 500.

The second and third stages employ supercontrol pentodes V302 and V303. The gain of these two stages is controlled by the gain control rheostat R848 at the indicator which varies the bias on the two tubes. These two stages as well as the succeeding stages have shunt condensers (C308, C312, etc.) to reduce their gain above 2,000 cycles per second and thus prevent the development of excessive amplifier hiss.

The remainder of the amplifier consists of two resistance-capacitance coupled triode stages feeding the output stage (beam tube V305, Figure 26). The output of the receiver is taken from the two secondaries of the output transformer T305, the first feeding the loudspeaker and the second the analyzer.

The regulated power supply on the receiver chassis is similar to that in the FM oscillator chassis (Figure 17). The receiver supply, however, does not have a cathode-follower driver corresponding to V103 for the regulator triode.

Regulated voltage is fed to all except the pentode output stage, which utilizes unregulated voltage. The receiver also supplies both regulated and unregulated voltage to the indicator for all except the cathode-ray accelerating voltage.

The receiver chassis has three potentiometers. Two of these, R302 and R305, are used to balance the injection voltage in the varistor detector. The third R336 is used to adjust the regulated voltage to the value required by the indicator circuits.

5.2.6 Analyzer

The analyzer is divided into two chassis (Figures 29, 30, 31, 32, 33, and 34) designated

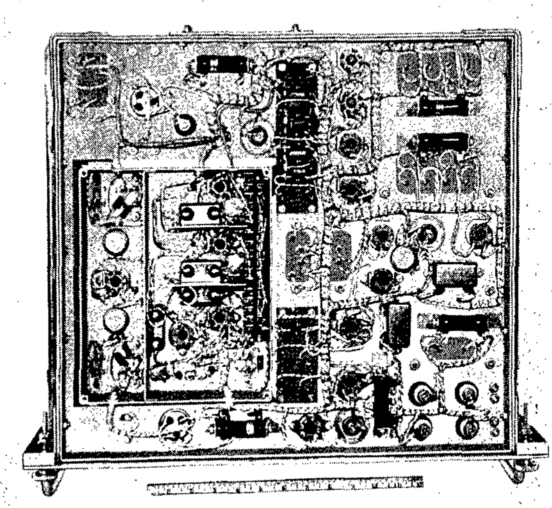


FIGURE 25. Receiver unit bottom view.

analyzer No. 1 and analyzer No. 2. It contains 20 band-pass filter networks with 20 associated detectors and a 20-element electronic switch. Analyzer No. 1 contains filters covering the band 500 to 1,250 cycles per second and the

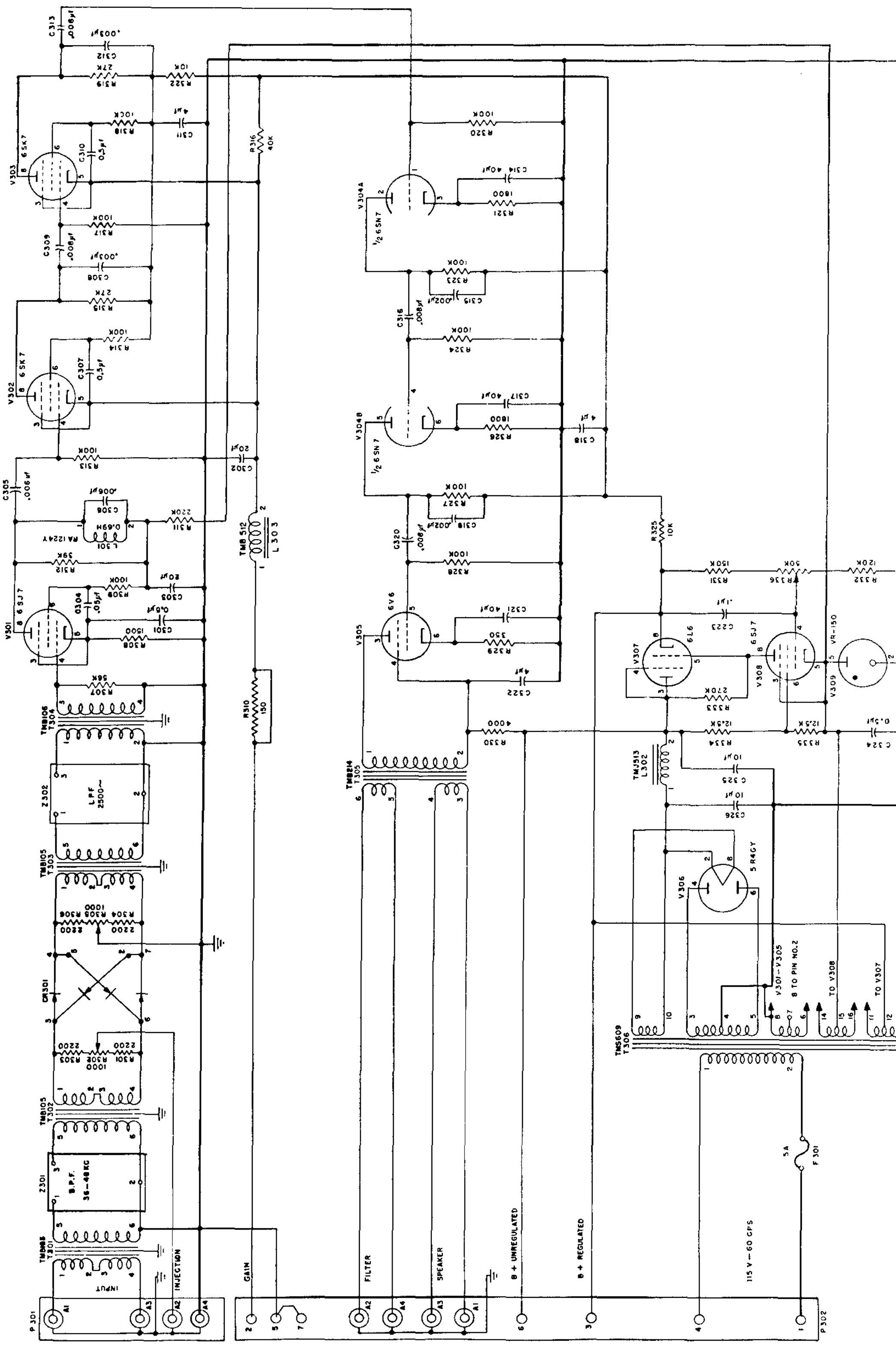


FIGURE 26. Receiver unit wiring diagram.

power supply for both chassis. Analyzer No. 2 has filters covering from 1,250 to 2,000 cycles per second and in addition the cathode follower output stage.

(Figure 12). The filter outputs are connected to corresponding detectors through potentiometers which are adjusted to equalize their gains.

A typical detector circuit is reproduced in Figure 36. The *RC* network consisting of R405, R404, and C404 in the plate circuit has a time constant of about 0.07 sec. Thus, noises of short duration, such as shrimp crackles, produce negligible output. On the other hand, the 0.5 mfd-10 megohm (C402 and R402) combination in the cathode circuit makes the detector sensitive to changes in input signal but insensitive to steady signals of long duration. For such signals the voltage developed across the

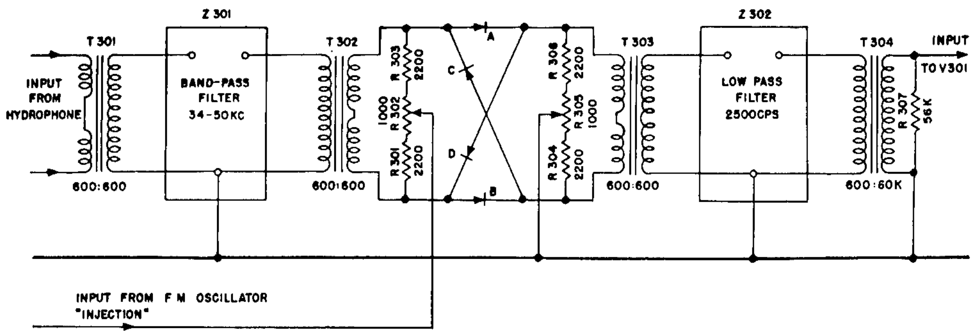


FIGURE 27. Receiver schematic input portion.

The individual filters are double-tuned, capacity-coupled circuits (Figure 35). The input of each is series-tuned so that one 50-ohm line from the receiver can feed all 20 filters in parallel. Each filter has a pass band 75 c wide. Widths are measured between frequencies on filter response curves at which the response is down 3 db from the peak. Channel No. 1 responds to signals of frequencies falling in the band 500 to 575 c, channel No. 2 from 575 to 650 c, etc.

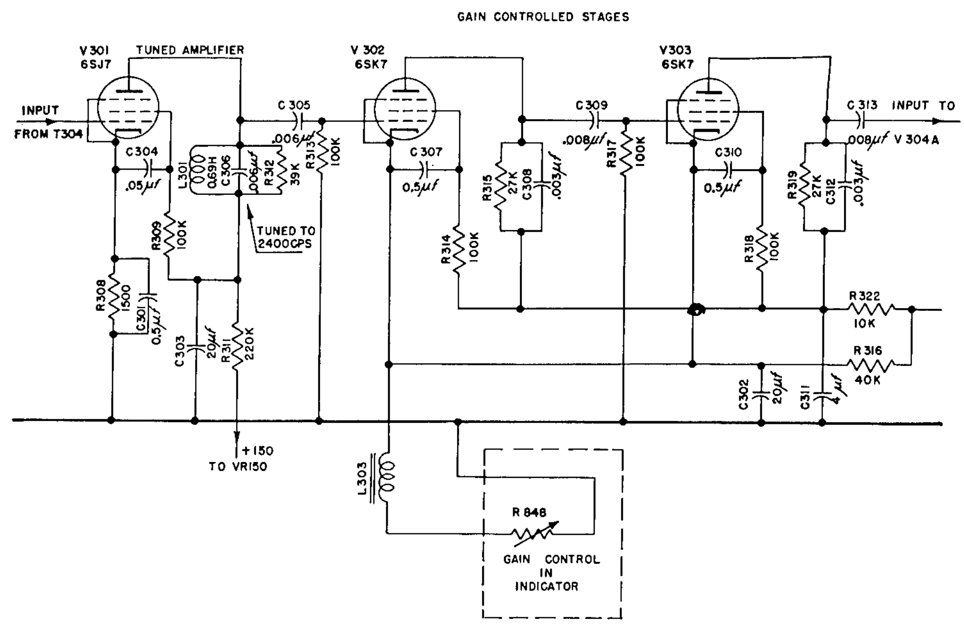


FIGURE 28. Receiver schematic, three-stage amplifier portion.

cathode resistor (R403) has sufficient time to charge the 0.5-mfd condenser through the 10-megohm resistance. This charge increases the bias on the detector tube, decreasing the plate current and thus decreasing the effect of the signal. In this manner, signals corresponding to water reverberation, which are substantially independent of the orientation of the hydrophone, produce an output that is reduced with respect to short signals of the same magnitude. Higher gains may thus be used without having reverberation light the screen. The system is therefore more sensitive to signals of the characteristic duration than to undesired disturbances of shorter or longer durations. The characteristic duration is about 1/3 sec and is determined by the time it takes the hydrophone beam (12 degrees wide) to sweep across a target at 6 rpm.

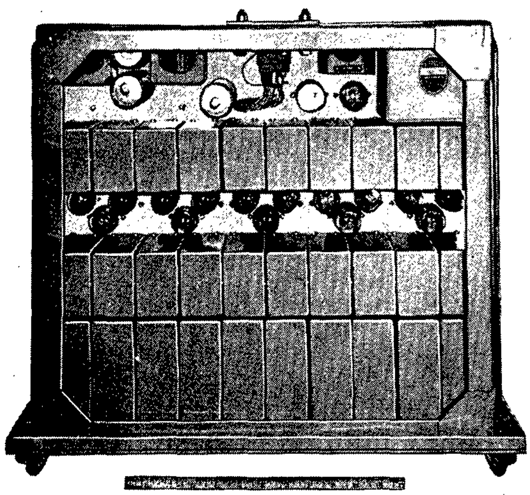


FIGURE 29. Analyzer No. 1 top view.

The condenser C401 (Figure 36) by-passes the 10-megohm resistance R402 insuring that all the signal voltage appears across potentiometer R401. The condenser in series with the input to the potentiometer (in the filter can) couples the filter to the detector without shorting out the 10-megohm resistance. Condenser C403 increases detection efficiency by reducing the impedance to signal frequencies.

The 20 switching tubes (Figure 37) are double triodes with their triode elements connected in series. The output of each detector reaches the indicator through the corresponding switch tube only when both of the latter's grids are at or near zero bias. The operation can be understood by considering one switch tube, for example, V406. The first grid of this dual tube is connected to one side of a 50-v, 60-c sinusoidal signal (terminal 4 of V406 to terminal 6 of Z421) while the second grid is connected at 180 degrees opposite polarity to the same signal (terminal 1 of V406 to terminal 2 of Z421). Only when the 60-c signal goes through its zero value are both grids at zero bias and the valve effectively open to pass signals. At any other time one or the other grid is biased beyond cutoff. The switch element is consequently closed (passes signal) twice for every cycle of the line voltage. The cathode (pin No. 6) of the first triode of V406 connects to the output of the corresponding detector (V401A). The plate of the first triode (pin No. 5) connects to the cathode (pin No. 3) of the second triode and is returned to the first cathode through a high resistance (R513) for stabilization. The plate of the second triode (pin No. 2) of all of the switch tubes connects to the common load resistance (R651) and through the cathode follower V616 to the indicator. If both triode elements of V406 are conducting then any voltage developed by the de-

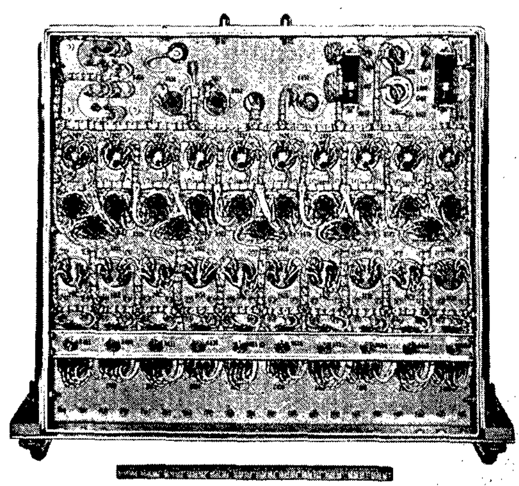


FIGURE 30. Analyzer No. 1 bottom view.

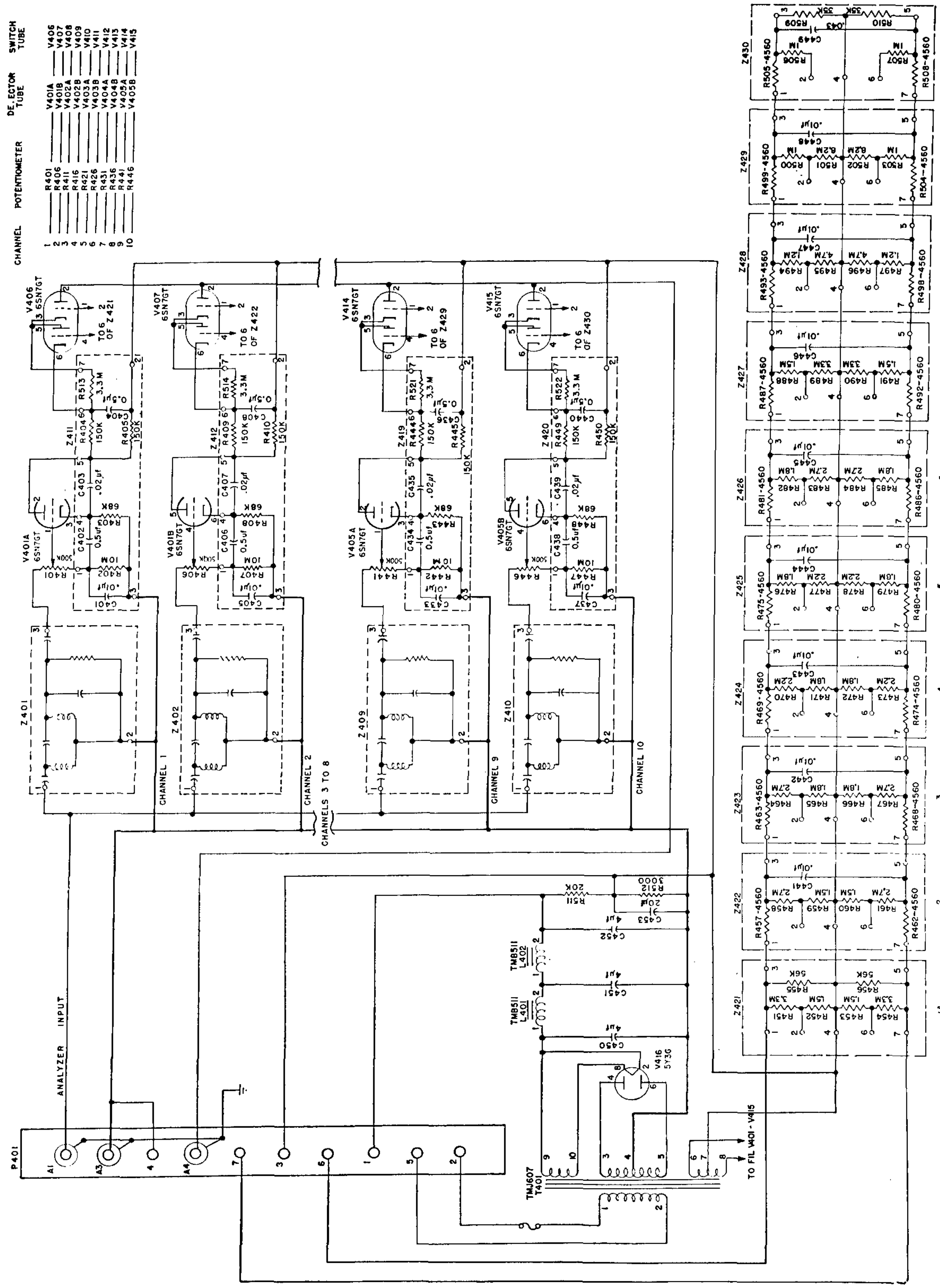


FIGURE 31. Analyzer No. 1 wiring diagram.

tector tube across condenser C404 is passed to the indicator. If on the other hand either triode element of V406 is cut off nothing is passed by it and thus condenser C404 is effectively disconnected from the output.

The switching sequence is established by means of a phase shifting network which is so constructed that the phase of the sinusoidal signal applied to successive switch tubes differs by 7½ degrees. Thus, the successive tubes form a synchronized switch system with V406 channel 1 (Figure 38) closed first, then 7½ degrees later V406 opening and V407 channel 2 closing, next V407 opening and V408 closing, etc., until all 20 switch points have been closed. The switch tubes, in effect, sample each of the signal storage condensers C404, C403, etc., for possible signals to be transmitted to the indicator. The closing of the 20 points requires 150 degrees of a voltage cycle leaving 30 degrees of the voltage cycle available for returning the cathode-ray trace to its initial position and applying a marker bug on the cathode-ray tube before V406 again conducts and the operation is repeated.

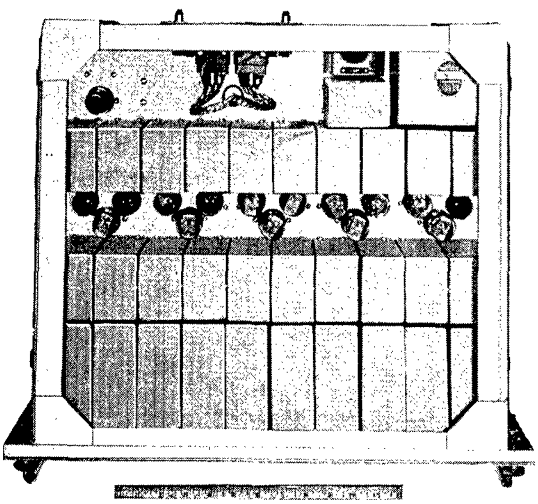


FIGURE 32. Analyzer No. 2 top view.

The phase shifting network (Figure 39) is fed from transformer T601. The network divides at the input, condensers C641 and C642 feeding the section in analyzer No. 1, and resistors R653 and R654 feeding the section in analyzer No. 2. The components are proportioned so that the voltage across Z421 leads the line voltage by 37.5 degrees while the voltage across Z621 lags the line voltage by this same amount. The voltage across Z421 is therefore 75 degrees ahead of the voltage across Z621. This is just the desired separation between channel 1 and channel 11. The remainder of the two network branches are identical, each giving 7½ degrees of phase shift per section. The voltage across Z621 follows the voltage across Z430 by 7½ degrees as well and the two branches form a continuous sequence. (See Figure 40.)

The phase shifting network contains dissipative elements and so is subject to attenuation; thus, the voltage across terminals 1 and 4 and 4 and 7 of Z421 (or Z621) is less than the supply voltage but more than the voltage across the output at terminals 3 and 4 and 4 and 5 of Z430 (or Z630). For this reason a bleeder is used across each element and the voltage to the grids is taken from these bleeders at terminals 2 and 6. These bleeders are proportioned so that they equalize the voltages applied to the switch tubes. (For resistor values, consult Figure 31 and Figure 34.) The bleeder is of high impedance to limit the grid current of the switch tubes.

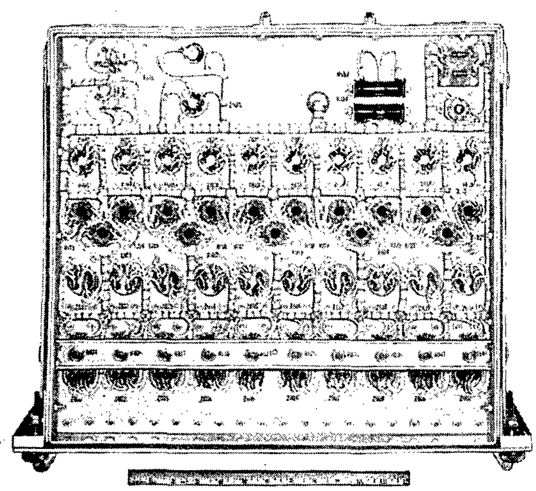


FIGURE 33. Analyzer No. 2 bottom view.

The phase shifting network is divided into

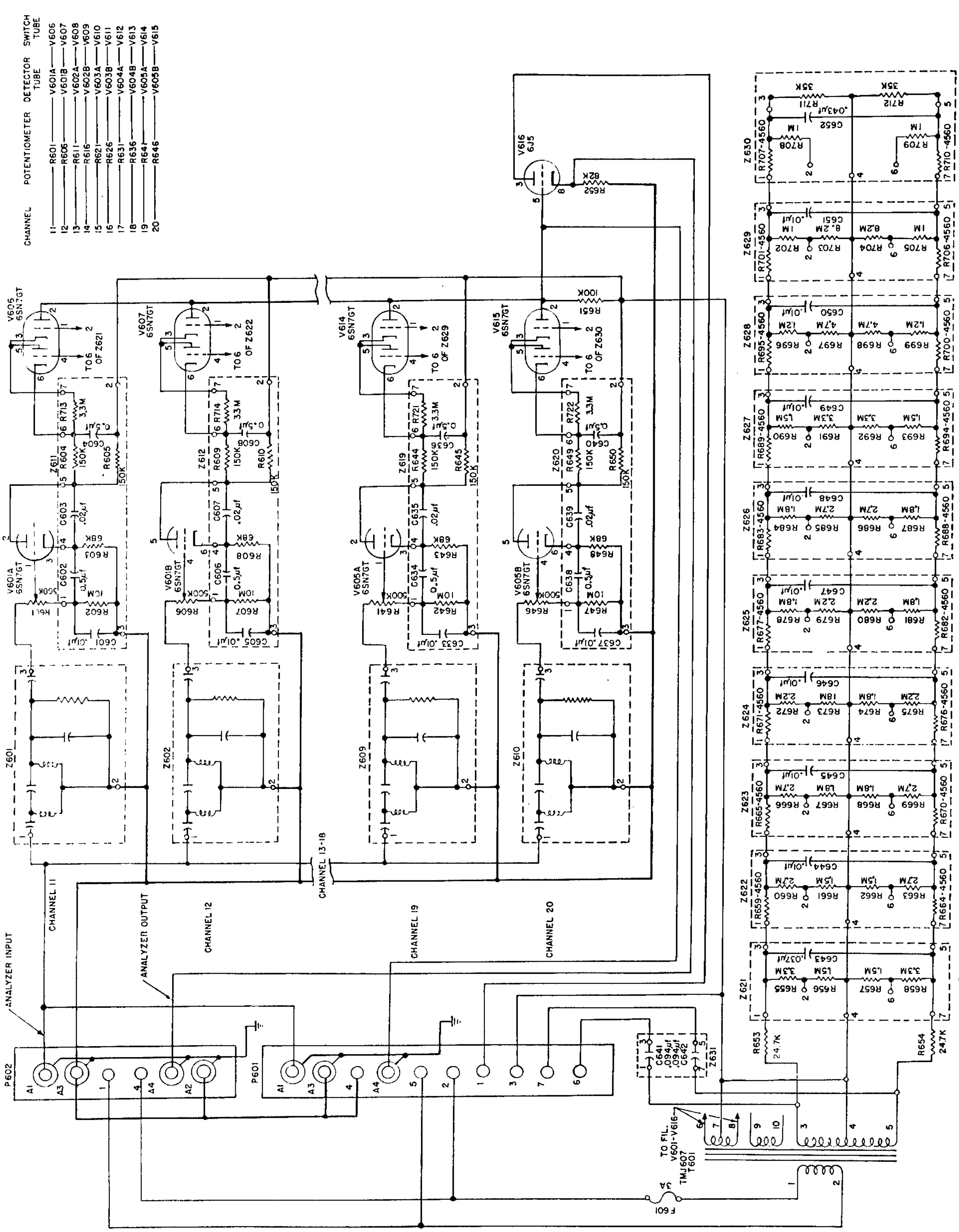


FIGURE 34. Analyzer No. 2 wiring diagram.

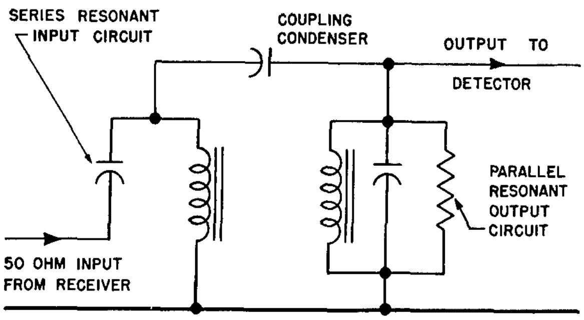


FIGURE 35. Analyzer schematic tuned filter portion.

two parts to reduce the attenuation and to allow the use of a lower voltage transformer.

5.2.7 Indicator and Loudspeaker

The indicator (see Figures 41, 42, and 43) and loudspeaker are small, compact units. They are intended to be mounted in the ship near the conning officer's operation position. The indicator contains a cathode-ray tube with its usual controls (vertical centering, horizontal center-

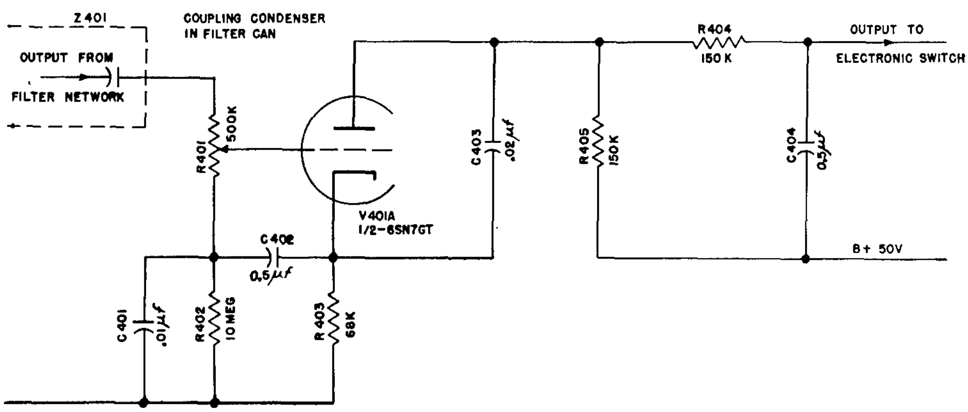


FIGURE 36. Analyzer schematic typical detector circuit.

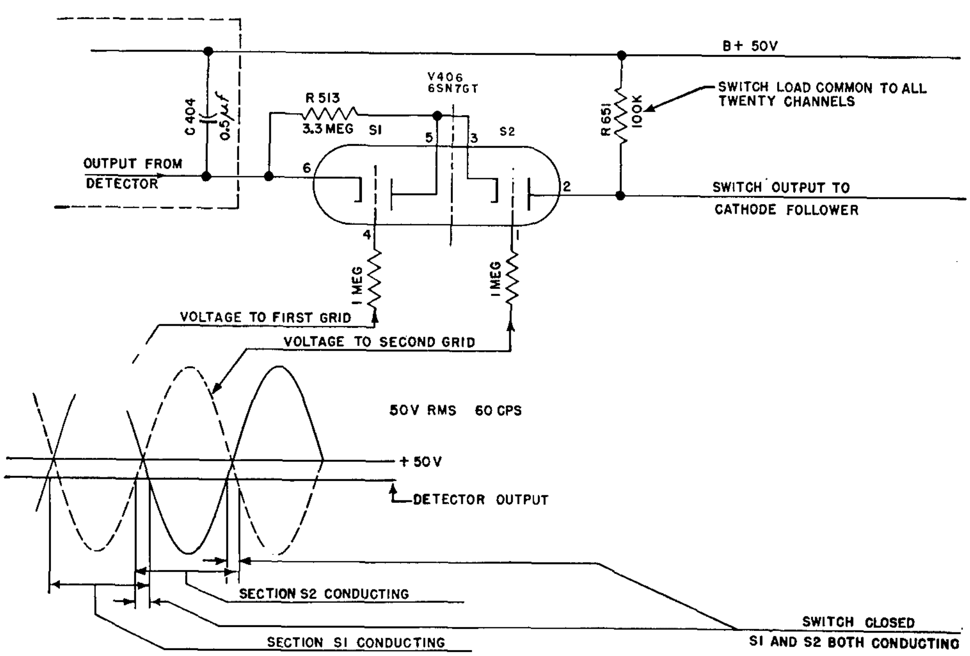


FIGURE 37. Analyzer schematic typical switch circuit.

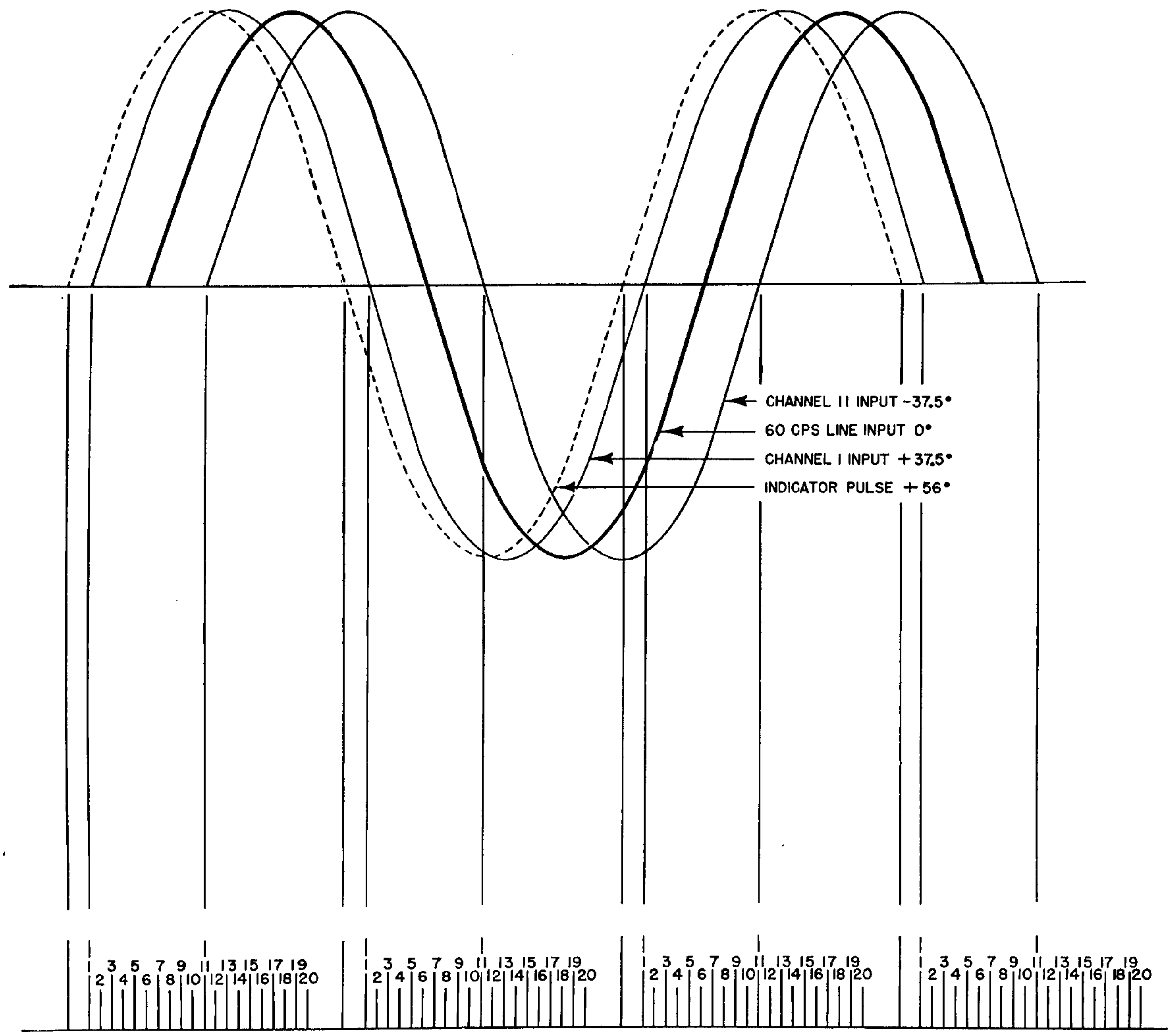


FIGURE 38. Indicator-analyzer synchronization diagram.

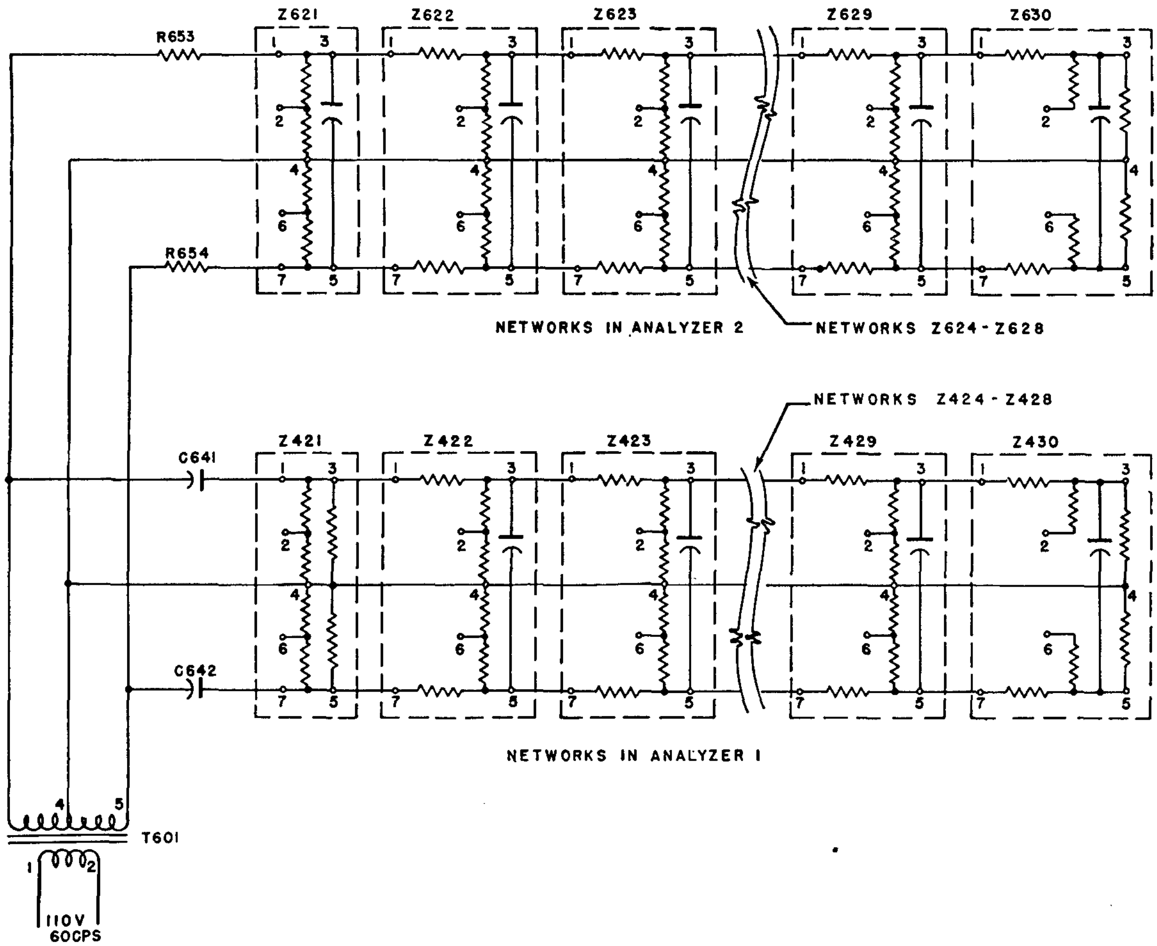


FIGURE 39. Analyzers No. 1 and No. 2: phase shifting networks.

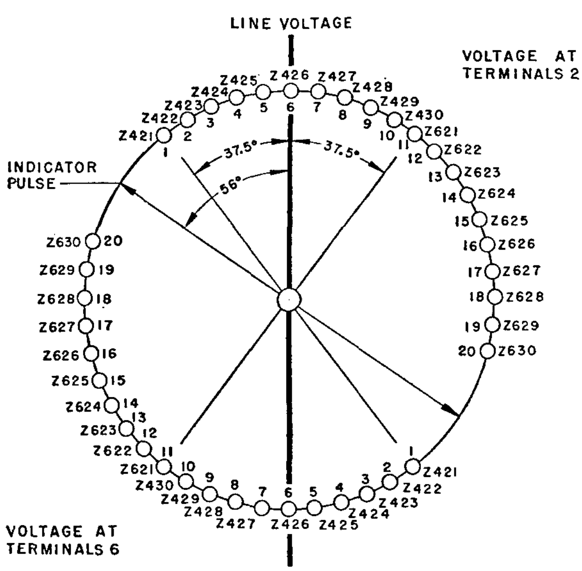


FIGURE 40. Analyzers No. 1 and No. 2: timing sequence.

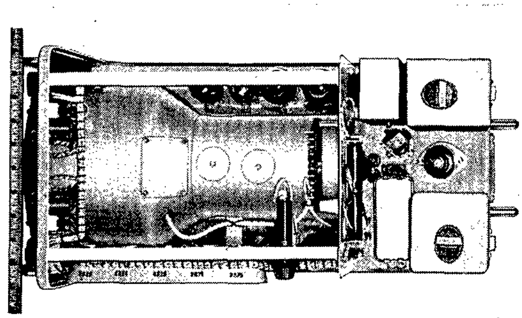


FIGURE 41. Indicator top view.

ing, amplitude, focus, and intensity) and in addition the operating controls for the entire system (the volume control, threshold control, range selector, the master and power amplifier switches, and a narrow scan-wide scan switch).

The indicator contains its own high-voltage supply, the necessary sweep circuits, and intensity amplifier. It obtains regulated and unregulated voltage for the sweep circuits from the receiver chassis (Figure 26).

The cathode-ray tube used is a 7BP7, a 7-in. tube with a long-persistence screen. The high-voltage supply for the accelerating potential is conventional in design.

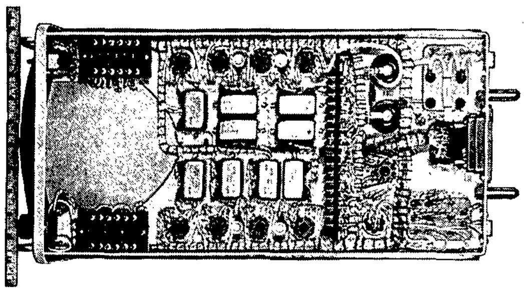


FIGURE 42. Indicator bottom view.

The radial sweep circuit contains a pulse generator, pulse shaper, and four sawtooth voltage generators feeding four deflection coil driver tubes.

The pulse generator (Figure 44) utilizes the double triode V801. Its grids are fed in push-pull from a 60-cycle per second source while its plates are connected in parallel. During the time that one or the other of the two grids is positive a large bias voltage is developed across the common cathode resistor R805 and condenser C809. This bias is sufficient to cut off the two triodes when the sinusoidal input goes through its zero value resulting in a positive pulse at the common plate terminals. At any other time the voltage at the plates is low as one of the triodes is conducting. The phase shifting network (R801 and R802, C801 and C802) is inserted to shift the phase of the sinusoidal signal input ahead by 56 degrees, placing the pulse about midway between the time of operation of channel 20 and channel 1 (Figure 38).

One-half of the double triode V803 is connected as a diode and is used to limit and shape the pulse while the other half is used as a cathode follower to couple the pulse to the sawtooth generators.

The sawtooth generators (Figure 45) utilize the double diodes V804 and V805 as switches (diagrammatically represented as knife switches). The positive pulse drives all four plates of the diodes positive. Since there is a low impedance between cathode and plate of a diode with the plate positive, the four cathodes are brought up to the same reference potential by the pulse, charging the condensers in their cathode circuits. At the end of the pulse the plates are driven negative, allowing the condensers to discharge at rates determined by the orientation of the sine potentiometer, which is linked to the soundhead. Since the rate of discharge of a particular condenser is proportional to the voltage differences between it and the corresponding terminal of the sine potentiometer, the four condensers discharge at rates proportional to the sine, cosine, minus sine, and minus cosine of the sine potentiometer orientation, and hence also of the soundhead orientation. (See Figure 46.)

The means by which the sine potentiometer is linked to the soundhead column is illustrated in Figure 47. The drive includes a mechanism for deliberately introducing backlash. The amount of this backlash is adjustable from 0 degrees to approximately 20 degrees difference in azimuth between the pointing of the soundhead and the indication on the screen. This mechanical backlash is introduced into the system to provide a delay in the time at which the bearing presentation on the screen is given to match that which is inherent in the analyzer detectors. If the bearing indication of a target at 000 degrees did not follow the training of the soundhead by the amount of the deliberate backlash, the soundhead would have moved to some other bearing (for example, 005 degrees) by the time that the indication reached the screen. To compensate for this the indication produced by the sine potentiometer and the cathode-ray trace are deliberately delayed. This

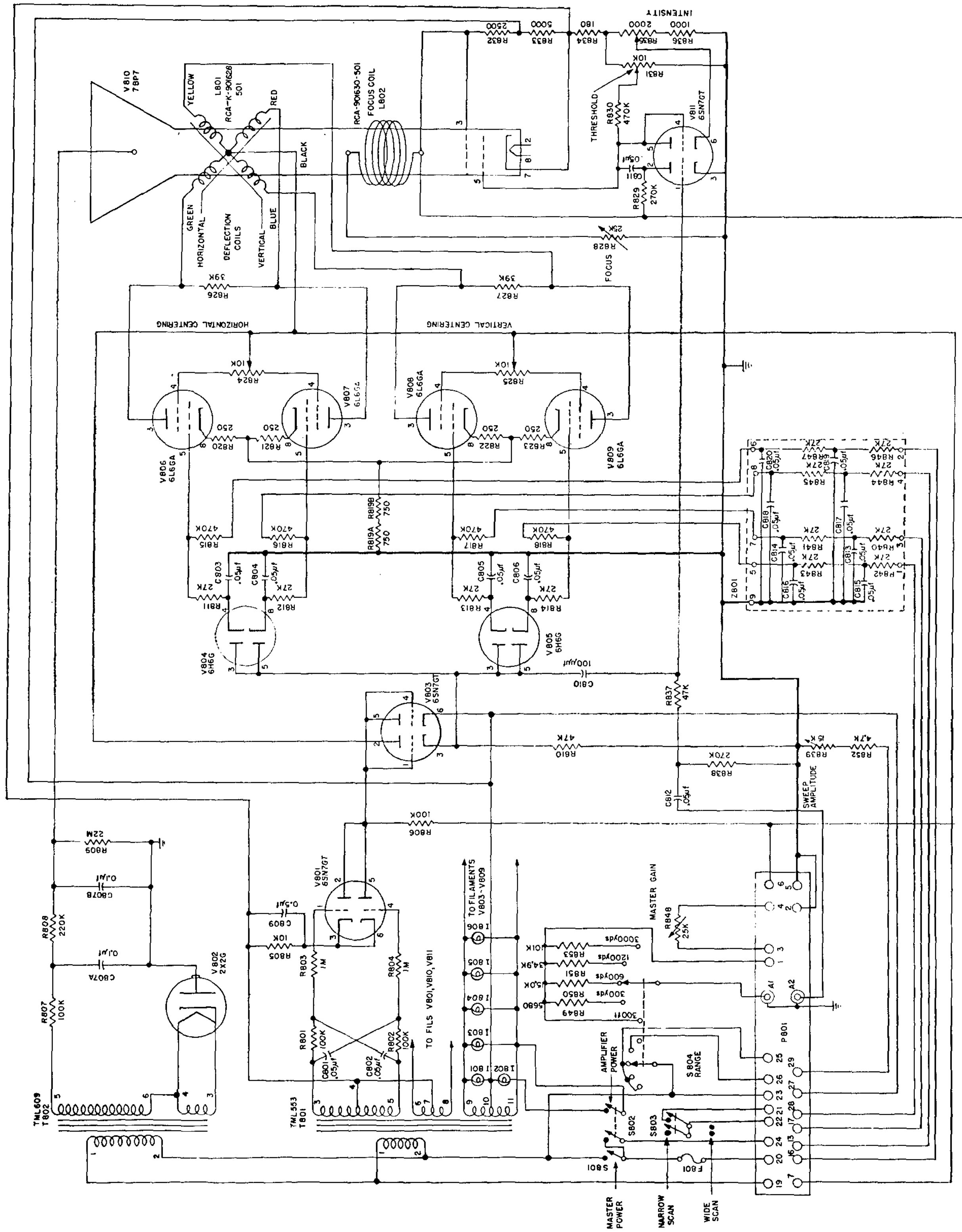


FIGURE 43. Indicator wiring diagram.

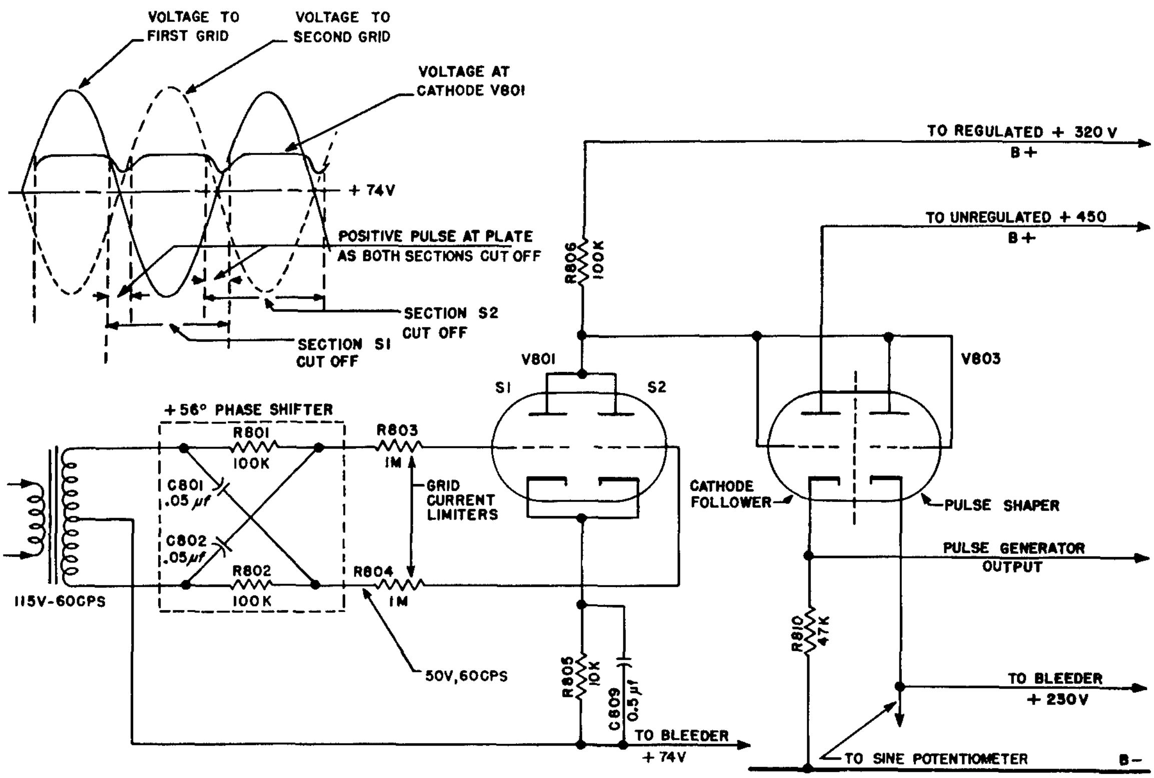


FIGURE 44. Indicator schematic; pulse generator portion.

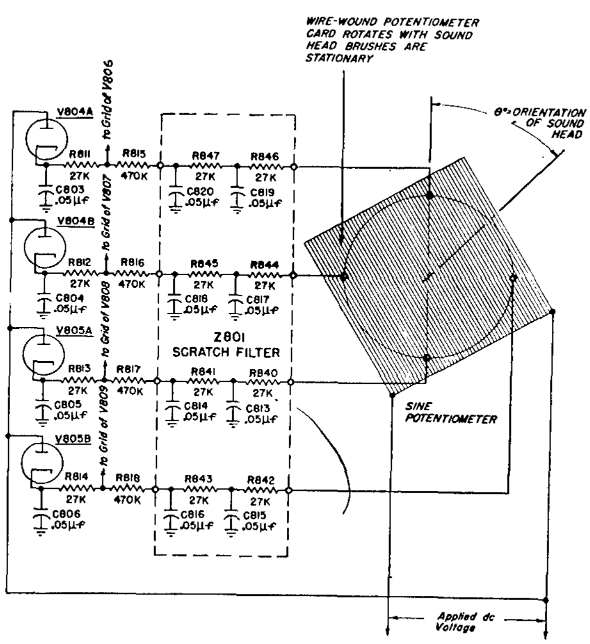


FIGURE 45. Sweep generator simplified diagram.

delay operates for both directions of training. Since the sine potentiometer does not usually furnish enough loading on the drive to take up the backlash reliably, the drive includes a friction drag assembly consisting of a spring, a metal, and a bakelite washer.

There are four deflection coil driver tubes. Each driver tube produces a current in the corresponding deflection coil tending to move the spot in one of the four major directions. The tubes in turn are driven from the appropriate sawtooth generator. Thus the tube tending to move the spot upwards (000 degrees) is driven by the generator whose output is proportional to the cosine of the angle the soundhead makes with the forward direction of the ship. The tube tending to move it to the right (090 degrees) is driven by the generator whose output is proportional to the sine of the angle, etc. The result is a sawtooth sweeping outward from the

center in a direction corresponding to the orientation of the soundhead (Figure 46).

The capacity of the analyzer to accept frequencies only from 500 to 2,000 c fixes the relationship between minimum and maximum ranges which may be portrayed on the CRO at one to four. For example, at a range setting for a maximum of 1,200 yd the system is cognizant of targets only down to a minimum range of 300 yd. In order that the CRO screen may faithfully portray this situation no target indication appears in the center of the screen.

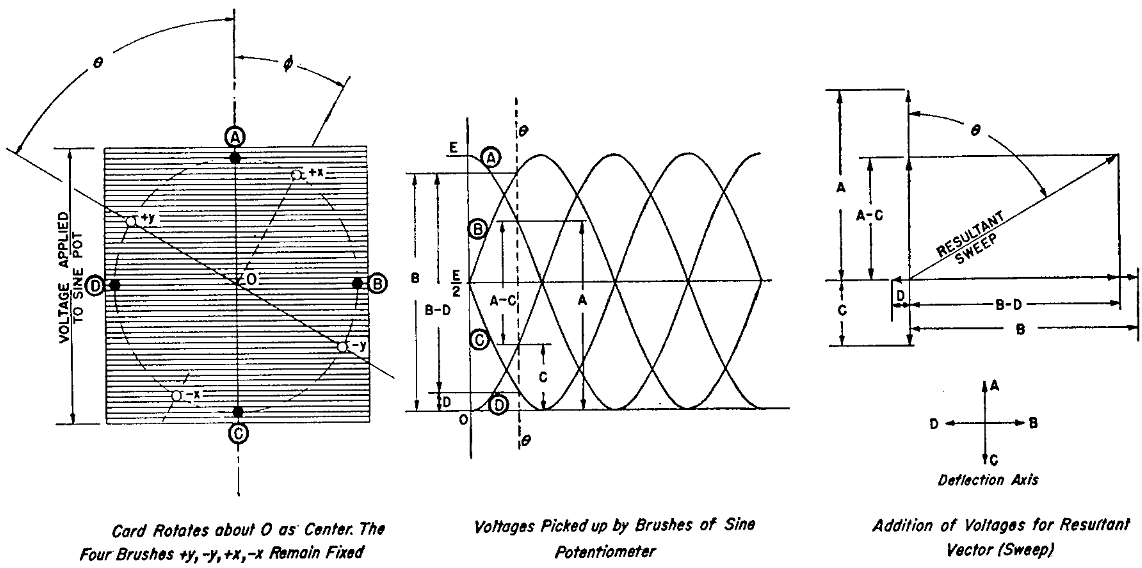


FIGURE 46. Sine potentiometer control of indicator sweep, explanatory diagram.

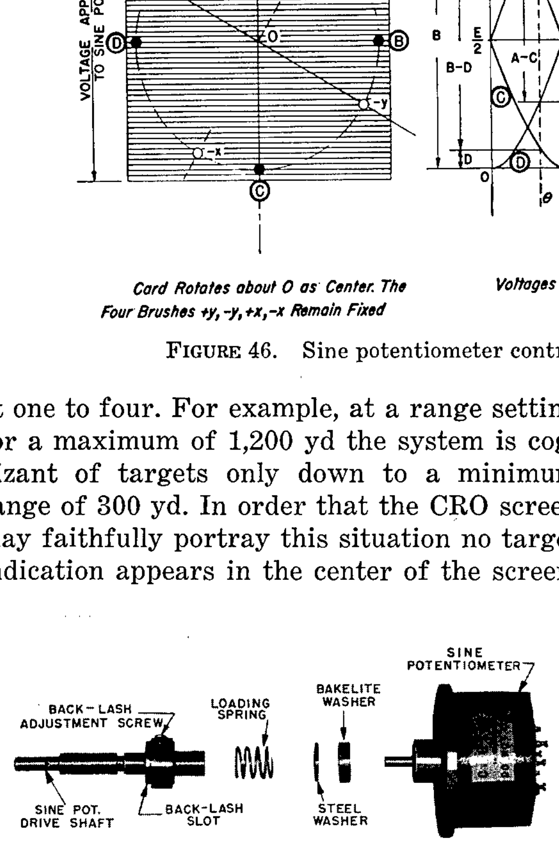


FIGURE 47. Sine potentiometer and friction drive.

This nonindicating area has, therefore, a radius equal to one-fourth that of the maximum radius of the sweep; and its extent is determined by the 0.27-megohm (R811, R812, R813, R814) and 4.70-megohm (R815, R816, R817 and R818) tap which superimposes on the sawtooth signal going to the grids of the driver tubes a small part of the sine potentiometer voltage. Connecting the grids directly to the sine potentiometer leads would remove all sawtooth voltage and leave a spot at a large radius from the center and at a bearing determined by the sine potentiometer position, but the use of the tap adds the two components in proper proportion to give the desired center hole. Omitting the 0.27-megohm resistors would start the sweep from the center itself.

The four deflection coil driver tubes have large cathode resistors (R820, R821, R822, and R823) to increase their stability. Centering of the pattern is accomplished by two potentiometers; R824 connected between screens of the horizontal pair of driver tubes, and R825 between screens of the vertical pair.

The intensity amplifier consists of a triode (one-half of V811), operating with zero bias, capacitively coupled (condenser C811) to the intensity grid of the cathode-ray tube (Figure 48). A diode (the other half of V811 with grid tied to plate) is used to limit the maximum voltage that the grid of the cathode-ray tube can reach, thereby limiting the maximum beam intensity. The intensity control R835, therefore, controls the minimum negative bias on the grid of the cathode-ray tube. The thresh-

old control R831 establishes the normal bias on the cathode-ray tube determining the minimum signal strength necessary to give a good image.

fier. The resulting differentiated pulse lights the screen just after flyback as the pulse output goes sharply negative.

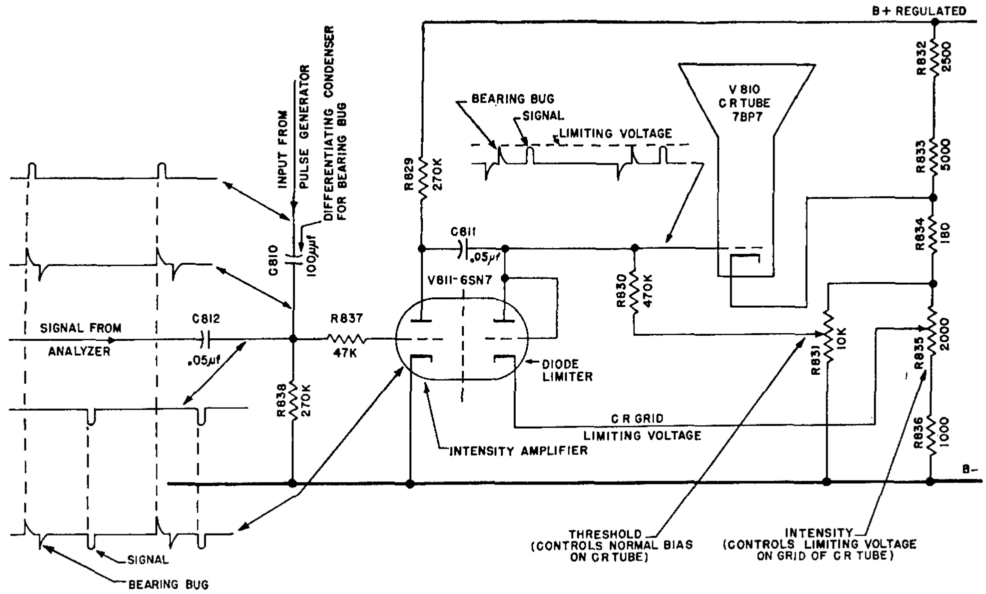


FIGURE 48. Indicator schematic: intensity amplifier portion.

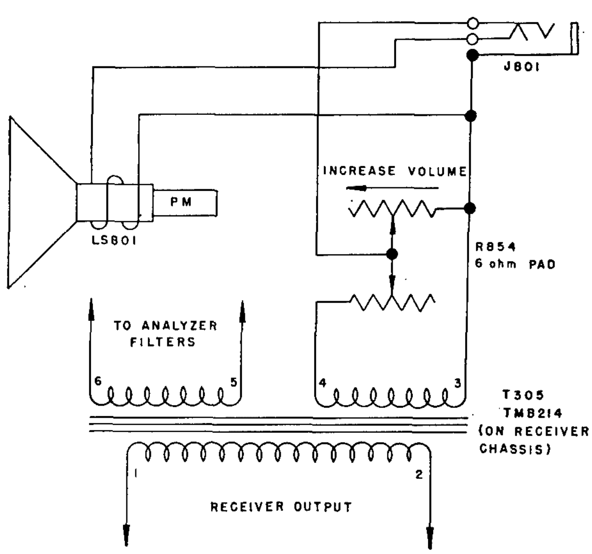


FIGURE 49. Loudspeaker schematic.

The direction-indicating bug is obtained by coupling the pulse generator output through a small condenser C810 to the intensity ampli-

The range switch on the indicator selects one of five values of resistance for the cathode return of the constant current tube (V106, Figure 18) in the FM oscillator. The lowest value of resistance is found in the FM oscillator and forms part of a decoupling network for the line. The other values are obtained by adding the resistor in the FM oscillator to one of four resistances (R849, R850, R851, and R853) found in the indicator.

The loudspeaker is mounted in a small metal box intended to be located near the indicator. It has on it an audio volume control and a jack for earphones. Insertion of an earphone plug removes the speaker from the system. (See Figure 49.)

5.2.8 Soundhead

The CJJ-78256 soundhead (Figure 50) is a cylinder 28 in. in length and $14\frac{1}{2}$ in. in diameter. It contains a transmitting projector and a receiving hydrophone mounted on a common framework enclosed in a steel shell having a sound-transparent rubber window on its face.

The projector is nearest the mounting studs. The free space within the cylinder is filled with D.B. grade castor oil. The soundhead mounts on Submarine Signal Company's standard 10½-in. QC-type flange. The zero azimuth of

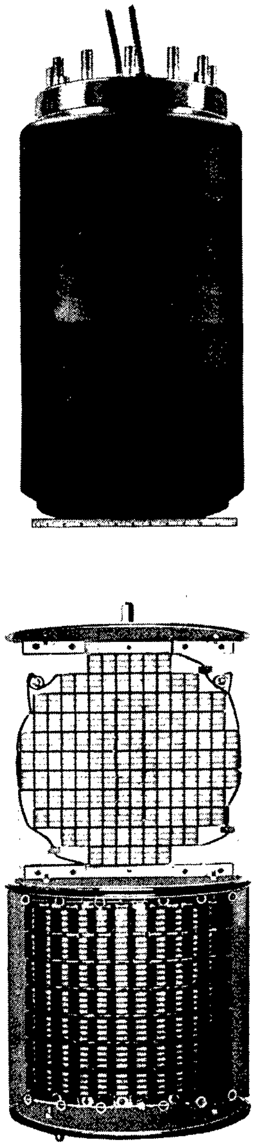


FIGURE 50. Soundhead and crystal motor assembly. Top, exterior view; bottom, cutaway view.

the beams of the projector and hydrophone is indicated by a $\frac{3}{16}$-in. hole found on the edge of the frame adjacent to the mounting studs.

The projector is of the crystal type, containing an array of ammonium dihydrogen phosphate [ADP] crystals. These crystals have the property of converting electrical energy into mechanical energy. The alternating increase and decrease in the length of each crystal's longitudinal axis (volume remaining constant) under the action of the electrical energy at the driving frequency imparts sound energy to the water at the same frequency. The projector is so constructed that it transmits sound principally into a horizontal fanshaped sector covering 80 degrees of bearing. The soundhead rotates so that the full 360 degrees of bearing can be covered.

At 42 kc the beam of the projector is approximately 12 degrees wide in the vertical plane and 80 degrees in the horizontal at 3 db downpoints (Figure 9). Two loading inductances are built into the soundhead.

The receiving hydrophone in the soundhead is very sharply directive. Sound energy impinging on the hydrophone from directions nearly normal to its face is transformed into electrical energy of the same frequency. The receiving hydrophone has a crystal motor 9 in. in diameter. It is constructed of 45-degree Z-cut ADP crystals.

The width of the principal lobe of the sound pattern of the receiving hydrophone is 12 degrees between −6 db points at 42 kc (Figure 9). Two inductances are used in series with the hydrophone to improve the response. They are mounted inside the soundhead. See Figure 51.

There is a junction box provided in the end of the soundhead. This is accessible by removing the plate on which the cable packing glands are located.

5.2.9 Soundhead Scanning Controls

CONTROLLER RELAY UNIT

The controller relay unit contains the motor reversing contactor, a pair of thyratrons with associated power supply to actuate the contactor coils, and auxiliary relays including the speed control relay. (Figure 52.)

Depressing the reversing control button connects terminal No. 10 (Figure 54) to the

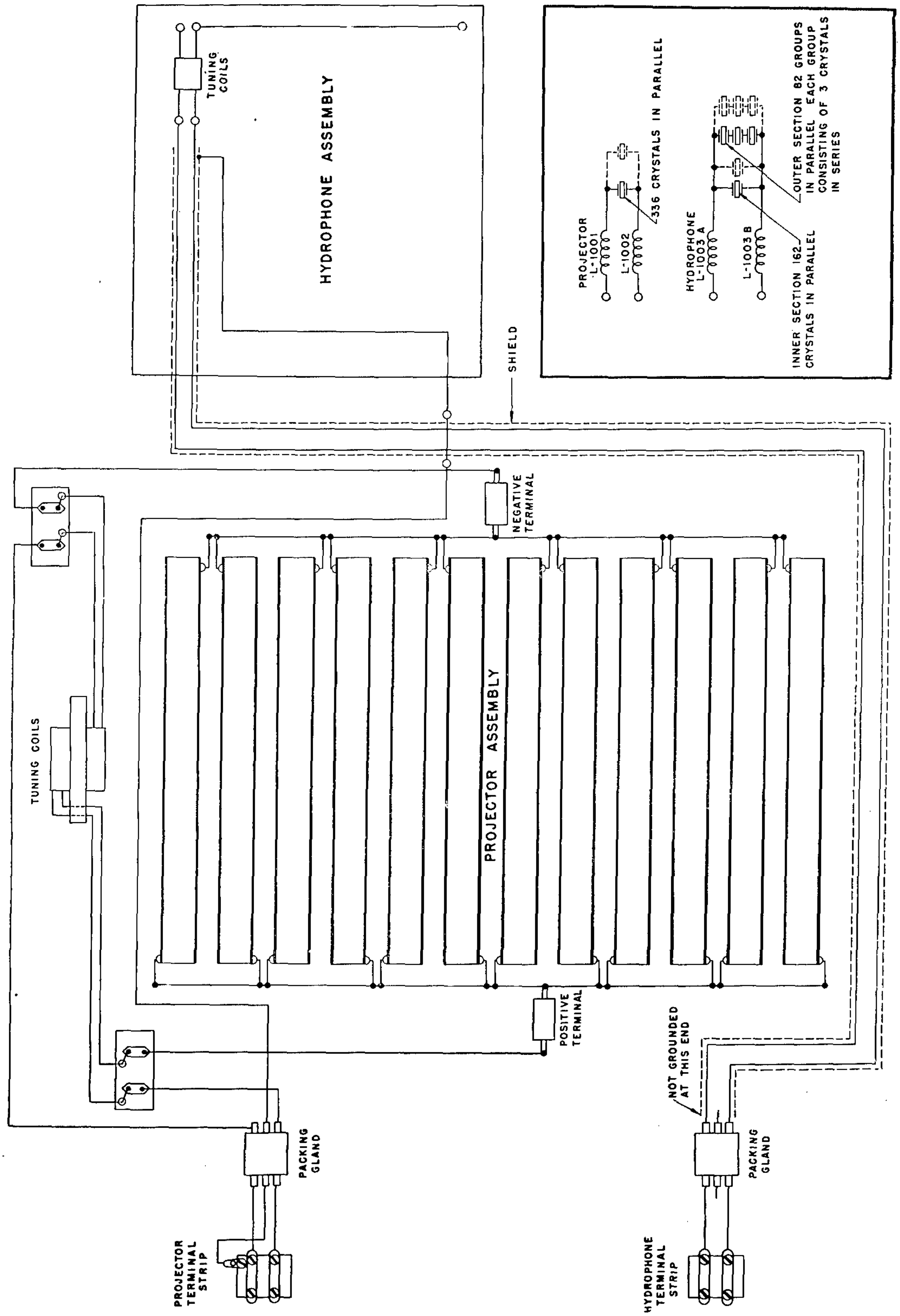


FIGURE 51. Soundhead wiring diagram.

ground, causing the thyratrons to close the opposite side of K901, thus reversing the column training motor. Limit switches prevent the soundhead column from completing more than three revolutions in one direction so that the cables are not sheared. As an added safety factor relay K902 is connected in series with the limit R908 and R909. This reduces the current through the operating solenoid to a low value, causing the contactor to drop out and stop the motor. The collapse of the field in the

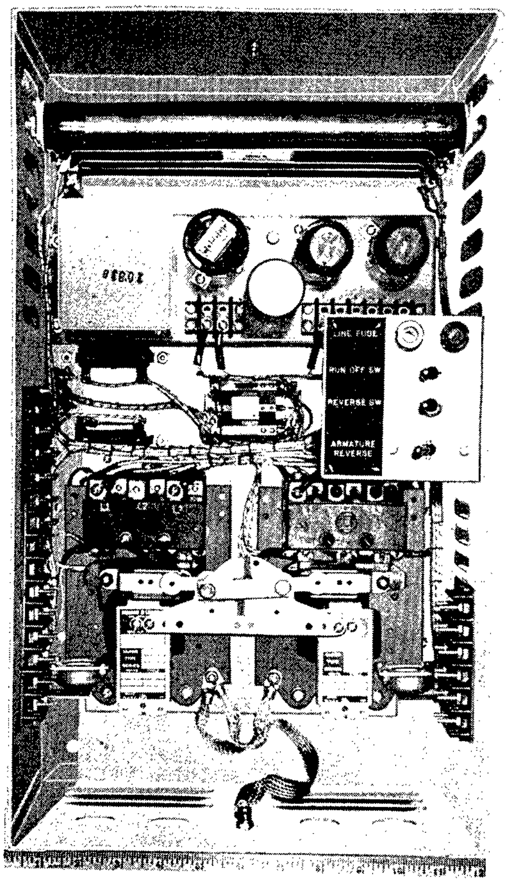


FIGURE 52. Column training motor controller relay unit.

magnetic circuit of the contactor produces a momentary pulse which extinguishes the operating thyratron and fires the other. The low value of current through this thyratron is sufficient to maintain the tube discharge, hence the first thyratron cannot refire. The motor may be restarted by closing S901 momentarily.

Resistors R911 and R912 are in series with the training motor armature on the 1,200- and 3,000-yd range scales, giving 3 rpm. On the 300-ft, 300-yd, and 600-yd range scales, the speed control relay K903 short circuits these resistors and the column rotates at 6 rpm.

LIMIT-SWITCH SECTÓR-SCAN ASSEMBLY

The limit-switch sector-scan assembly performs two functions. It prevents the hydrophone and projector cables, which emerge from the shaft and are attached directly to the terminal boxes on the bulkhead, from being twisted off through continued rotation in one direction. Column rotation is limited to three turns for which sufficient slack is allowed in the cable installation. In addition, when the sector scan toggle switch on the indicator is set to *Narrow Scan* the assembly acts to reverse the soundhead, automatically covering a sector of predetermined width (up to 120 degrees).

The limit-switch sector-scan assembly consists of two sections housed in a bronzed casting. Four microswitches are incorporated; three in the limit-switch section and one in the sector-scan part of the assembly. Each of the four switches performs a separate function (Figure 53).

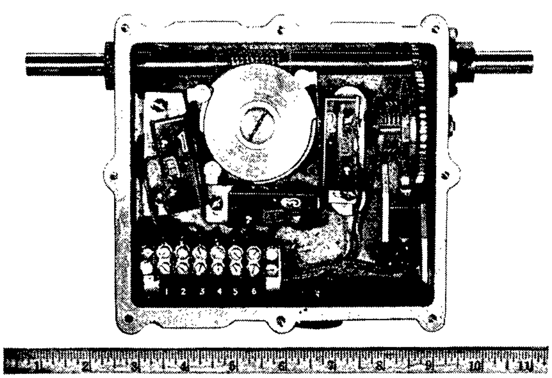


FIGURE 53. Limit-switch sector-scan assembly.

As explained, if the reversing control button is depressed the thyratrons will switch and the

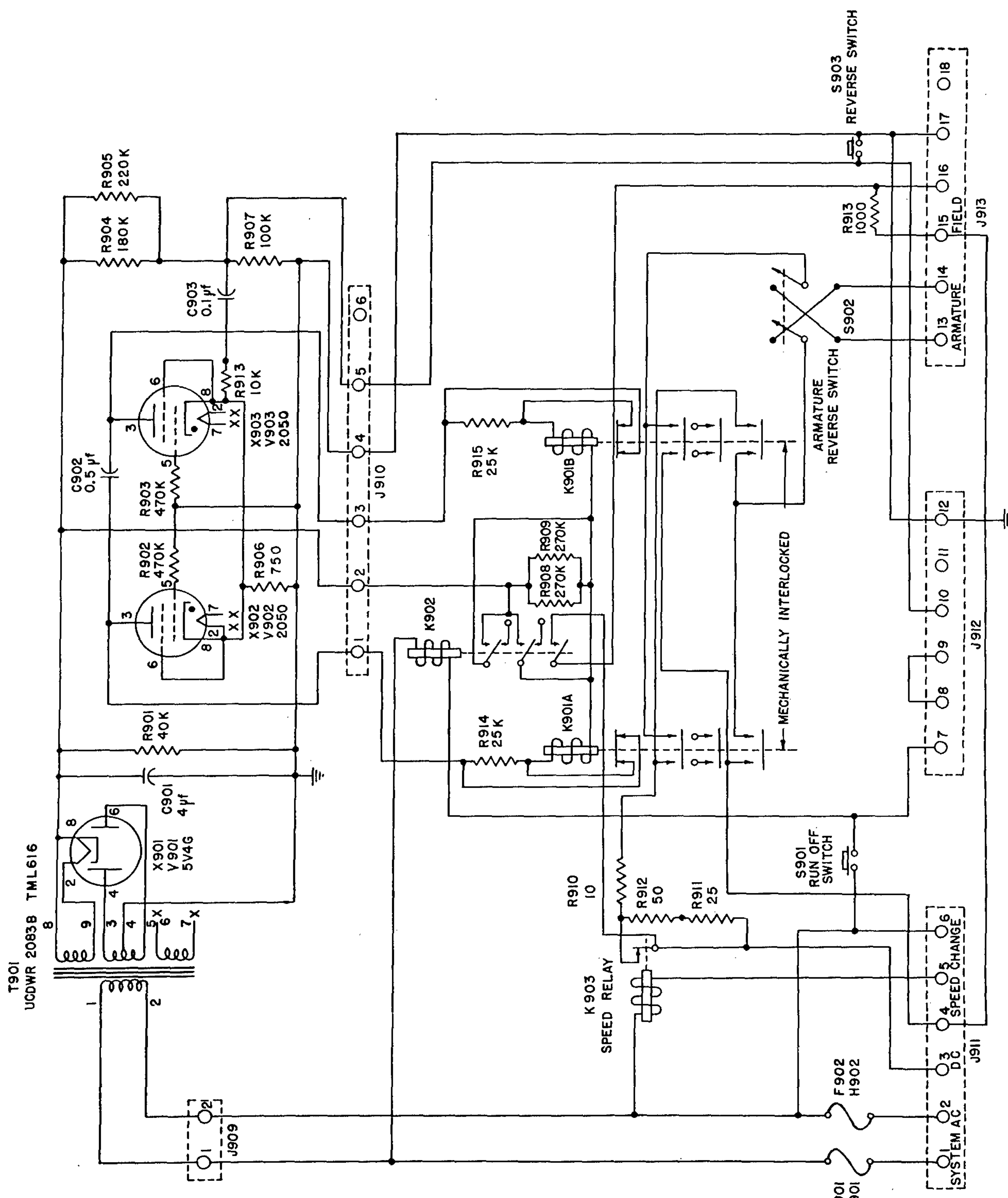


FIGURE 54. Motor controller unit wiring diagram.

opposite side of relay K901 closes, reversing the direction of motor rotation. Microswitch No. 2 (the limit switch) when actuated provides this connection at the end of three revolutions in one direction. The remote control push-button near the indicator also connects No. 10 to No. 12 (of J912) as does microswitch No. 4 (the narrow-sector switch) when the sector-scan toggle switch on the indicator is in the narrow-scan position. Microswitch No. 1 (the disable switch), on the other hand, is in series with the remote control push-button and microswitch No. 4, and serves to disable the functioning of these latter controls near the end of the three full turns where they could interfere with the limit switch, microswitch No. 2. Microswitch No. 3 (the protective switch) is in series with the coil of the relay K902. K902 disconnects both the motor field and the armature if both the disable and limit switches fail to function.

Chapter 6

TRANSDUCER DEVELOPMENT

Early in 1942, the UCDWR concerned itself with research, development, and small-scale manufacture of transducers. Because of limitations on time and manpower its attention was concentrated on transducers utilizing Rochelle salt [RS] and later ammonium dihydrogen phosphate [ADP] crystals; very little work with electrodynamic or magnetostrictive devices has been done.

Since the early stages of the work, a number of experimental transducers of various types were turned out which implemented the development of the FM systems program through Cobar, Pribar, Subsight, and Fampas. Trials of these early transducers with the FM systems just mentioned led to the development of specifications to be met by the final transducer evolved for QLA-1 and to the discovery of the transducer design problems to be overcome.

6.1 THE TRANSDUCER PROBLEM

The transducer development program did not start out with a full-fledged set of basic design considerations describing the ultimate transducer for FM systems. The process was evolutionary with sometimes the FM system pointing the way to improvement in transducers and at other times the transducer indicating opportunities for improvement of the system.

In the light of present knowledge, it may be stated in general that the transducer for use with a QLA system should have the following characteristics:

1. Projector power output of 110 db above 1 dyne per sq cm at 1 yd.
2. Frequency response flat throughout the operating band of the system. At the present state of the art, this requirement is met by a transducer which gives a flat response within ± 3 db over a frequency band of 10 to 12 kc somewhere between 20 and 50 kc.
3. Rigidly established directivity characteristics dependable throughout the operating band. Except in the case of 360-degree projectors a high degree of side lobe suppression is important.
4. A low level of crosstalk between projector and hydrophone.
5. High efficiency in conversion of electrical to mechanical (sonic) energy. This subject is closely related to loss of electrical energy by conversion into heat energy within the crystal itself.
6. Temperature independence: the characteristic functions of the transducer should be independent of the temperature of the medium or of the crystals themselves and the crystals should be able to withstand relatively high temperatures without breaking down.
7. Provision for the inclusion of tuning coils or other matching networks.
8. Mechanical ruggedness sufficient to withstand war service aboard various naval vessels.

6.2 BASIC DESIGN CONSIDERATIONS

6.2.1 Physical Structure

A transducer must contain a large number of crystals in order to produce the desired output into the water as a projector, or electrical power as a hydrophone. Large numbers of crystals are also required, in certain applications to produce the desired directivity pattern.

The crystals are mounted on a steel backing plate. The thickness of the backing plate as well as the length of the crystals is a factor in the production of a specific resonant frequency. A properly chosen thickness for the backing plate can result in a saving of crystal material.

Both Rochelle salt and ADP crystals are soluble in water. Contact with sea water would not only destroy the crystals themselves, but because of the high voltages usually applied to them, the presence of sea water in even minute quantities would result in electrical failure in the transducer. Because of these facts the crystals and backing plate must be housed in a strong watertight case some portion of which serves satisfactorily as an acoustic window.

Design requirements arising from the necessity of streamlining the housing and securing proper directivity in the projector and hydrophone generally prevent the crystals from being in actual contact with the acoustic window. Consequently a medium must be provided to transmit the sound from the crystals to the window. An electrical grade of castor oil so far has proved satisfactory for this purpose.

The piezoelectric nature of the crystals themselves requires that electrodes connecting them with the power source (or receiver in the case of the hydrophone) must be attached to the proper crystal faces and leads brought out from them. The leads may be connected in series or parallel in the correct phase and brought up to a cable which enters the housing of the transducer through a watertight packing gland. It is convenient to make connections to the cable in an air cavity, and the backing plate is sometimes used as a bulkhead between this air cavity and the castor oil surrounding the crystals themselves.

The operating characteristics of any transducer are greatly altered if parts of the transducer, other than the acoustic window, become acoustically coupled to the crystal array. For example, to diminish this coupling between the housing and the crystal array, acoustic isolation material is distributed throughout the soundhead structure in sheets, washers, grommets, etc. The two isolation materials found most satisfactory for this purpose are Corprene (a trade name for a series of compounds composed of ground cork and rubber and made by Armstrong Cork Company, Lancaster, Pennsylvania) and foam rubber. As distinguished from sponge rubber whose cells intercommunicate a true foam rubber must be used in which the cells are isolated from each other. One such material is known by the trade name of Celltite, manufactured by Sponge Rubber Products Co. Both of these types of acoustic isolation material contain large quantities of gas distributed throughout their structure in small bubbles.

When voltage is applied to the two electrode faces of a crystal the other four faces move. At any instant the crystal is stretched in one direction and contracted in the other, volume remaining constant. Thus, opposite pairs of faces (except the electrode faces) vibrate in phase; but the two pairs of faces are 180 degrees out of phase. If one of the moving faces is attached to a steel backing plate, the desired radiation emanates from the face opposite the backing plate. Unless suitably baffled, the remaining two faces would radiate out-of-phase and tend to cancel the desired radiation. For this reason these out-of-phase faces are covered by Corprene or other suitable substance which is a sound isolating material.

Crystals are affixed to the backing plate with one of several types of commercially available plastic adhesives. The adhesive joint must be comparable in strength to the crystals and steels involved and must be sufficiently flexible to accommodate the difference between temperature-expansion coefficients of the steel backing plate and the crystals mounted thereon. The sound conductivity coefficient (ρ-c) of the adhesive is considerably different from those of crystals or steel; hence, the adhesive joint must be thin enough that this difference in ρ-c does not prevent the system from responding as a unit in the conversion of electric energy into sonic energy. The characteristics of the adhesive must not permit cavitation within its structure under the influence of the high pressures (particularly negative pressures) developed by the piezoelectric activity of the crystals. Although the pressures created are high the piezoelectric-induced changes in the dimensions of the crystal surface cemented to the backing plate are so minute (even in relation to the small cross-sectional dimension of the thin adhesive layer) that shear forces are not a problem.

6.2.2 Directivity

The directivity pattern of a transducer is primarily determined by the size of shape of the array measured not in inches but in wavelengths of sound in the ocean at the frequency at which the pattern is observed. (Thus, the pattern of any transducer changes with frequency.) The directivity pattern of a transducer is further determined by the variations in phase and amplitude of vibration among different parts of the crystal array.

A transducer employing a plane array of crystals connected in phase and vibrating at a uniform amplitude is fairly directional if the array is more than one wavelength wide in any dimension. It has one main lobe and several side lobes of lower intensity.

For a given shape of array (circular, square, etc.) uniformly driven, the number of decibels by which the various side lobes are below the main lobe is fixed by the phasing and amplitude characteristics just mentioned. For example: first side lobes of a circular array are the most intense and are 17 db below the main lobe.

To reduce further the intensity of side lobes a nonuniform arrangement of the crystal motor is employed. Variations of phase or amplitude across the array reduce the prominence of the side lobes as compared to those of a uniform array. This technique is called lobe suppression. Because of the difficulty of arranging phase variations across a crystal array, lobe suppression is generally accomplished by nonuniform arrangements of crystal motors within the array and by variations in the vibration amplitudes of the crystals, keeping them all in phase.

6.2.3 Crystals

At the beginning of World War II, all synthetic crystal transducers built in this country for the Navy, employed 45-degree X-cut Rochelle salt. In late 1941, 45-degree, Y-cut Rochelle salt became available. Subsequently, ADP crystals were developed and produced in a quantity which made it possible to replace Rochelle salt crystals with the ADP in most new construction.

Although the dielectric constant of 45-degree X-cut Rochelle salt is very large, this cut suffers from temperature dependence, nonlinearity, and internal losses. A transducer constructed of 45-degree X-cut Rochelle salt crystals is relatively unstable; its behavior depends on temperature and applied voltage. Because of this instability, it is not possible to use a tuning network to match the transducer to an amplifier. Furthermore, because the impedance of a given crystal is a function of temperature, and because variations among crystals are not uncommon, a few crystals may carry all the load in a given installation. This leads to unacceptable directivity patterns, unpredictable frequency response, and frequently to electrical or mechanical failure.

The 45-degree Y-cut Rochelle salt crystal is linear, substantially independent of temperature, and exhibits relatively low internal loss. The 45-degree Y-cut Rochelle salt transducer, however, has a relatively high impedance.

All Rochelle salt crystals are destroyed at relatively low temperatures. ADP is a marked improvement in the respect that it is safe to 100° C as compared to the destruction point of RS crystals at 49° C. Forty-five-degree Z-cut ADP crystals are nearly temperature independent, linear, exhibit no internal loss, can radiate higher sound intensities than the Rochelle salt crystals, and exhibit a somewhat lower impedance than the 45-degree Y-cut Rochelle salt.

The prime requirement in a piezoelectric crystal is a close coupling between its electrical and mechanical (acoustic) characteristics. Other features of importance are: mechanical strength, chemical stability, physical stability over a wide temperature range, independence of electrical and mechanical properties (particularly impedance and resonant frequency) from temperature and applied power, and low hysteresis.

6.2.4 Backing Plates

A piezoelectric crystal is effectively a rod vibrating in the direction of its longitudinal axis. The crystal's lowest resonant frequency is the one normally utilized. Without a backing plate this lowest resonance would occur at that frequency at which the wavelength of sound (in the crystal) is twice the length of the crystal's longitudinal axis. In other words, lowest resonance is obtained with the crystal acting as a half-wave system. With a suitable joint between the crystal and its backing plate, the backing plate adhesive-crystal assembly behaves as a unit in performing the functions of a half-wave system. Thus, with a backing plate of a thickness equal to one-fourth the wave-

length of sound (in steel) on which are cemented crystals whose normal length to the backing plate is one-fourth the wavelength of sound (in the crystal), the system acts as a unit exhibiting the same resonance as that exhibited by the one-half wave length crystal acting alone.

Since this phenomenon is valid for any and all variations in the thickness of the steel backing plate and the crystal length, it would seem logical when considering the low cost of steel as compared to crystals to make the system consist mainly of steel backing plate to which a very thin crystal would be cemented. There are two considerations which make this impracticable: (1) Crystals have a low Q as compared to steel. The wide band operation of FM systems requires a low Q in the transducer; hence, the proportion of the half-wave system which may be comprised by the steel backing plate is limited. (2) At the 42-kc average frequency of FM systems, a half wavelength is about 2½ in. in steel, about 1 in. in RS crystal, and about 1½ in. in ADP crystal. Hence, as much of the half-wave system as economically feasible is composed of crystal to avoid the extremely cumbersome assembly which would result were the major portion of the system in steel.

6.2.5 Response

One or two response curves do not suffice to describe a transducer or to compare transducers. For a proper understanding of a transducer, one must examine several of the following curves:

As a projector. (1) sound output for constant applied voltage, (2) sound output for constant power expended, (3) sound output with an idealized matched amplifier, (4) sound output when driven by an actual amplifier with matching networks.

As a hydrophone. (1) open circuit voltage for constant incident plane wave pressure, (2) power delivered to a matched load for constant incident plane wave pressure, (3) self-noise open-circuit voltage for zero incident pressure.

Transducer. (1) complex impedance, (2) directivity patterns in many planes.

In general, all of the response curves mentioned above except constant power as a projector and self-noise as a hydrophone show a maximum in the vicinity of resonance if the transducer is efficient. The constant-power projector curve of a perfectly efficient transducer is a smooth curve rising with frequency as the transducer becomes more directional. A peak in the curve indicates a variation of efficiency with frequency.

Maximum efficiency and hence maximum output of a transducer are generally achieved at or near its resonant frequency. For various reasons the lowest resonant frequency is almost invariably the one used in actual practice and little use is made of higher resonances.[a] Because of resonance a transducer delivers a specified output only over a restricted band of frequencies. This bandwidth is more or less inherent in the crystals but is also dependent upon the details of design and construction and upon the method of operation (i.e., type of amplifier, matching networks, etc.). Because of the importance of resonance as a factor influencing efficiency and maximum output it is advisable that any transducer be so designed and constructed that its resonant frequency falls within the bandwidth at which the FM system is expected to operate.

In addition to the resonant characteristics inherent in the crystals, additional design construction details, including length of crystals, their cementing to the backing plate, and the thickness and nature of the backing plate, all influence the resonant frequency at which the transducer operates.

6.3 TRANSDUCER DEVELOPMENT

Most of the transducers used in the early development of FM systems had some features in common: (1) Rochelle salt crystals were used as the active elements, (2) the crystals were mounted on a steel backing plate with suitable insulation, (3) the exterior case was steel with a rubber acoustic window, (4) the crystal array was flat, and (5) the beam patterns were rather directional. A transducer typical of these early

[a] See Division 6, Volume 12.

units is shown in Figure 1. The common fault of these early transducers was low efficiency, and most of the difficulties arising from their use could be traced to this cause. The resistive term in the complex impedance was unpredictable, thus delaying electronic design of matching networks until the individual transducer was manufactured and available for test.

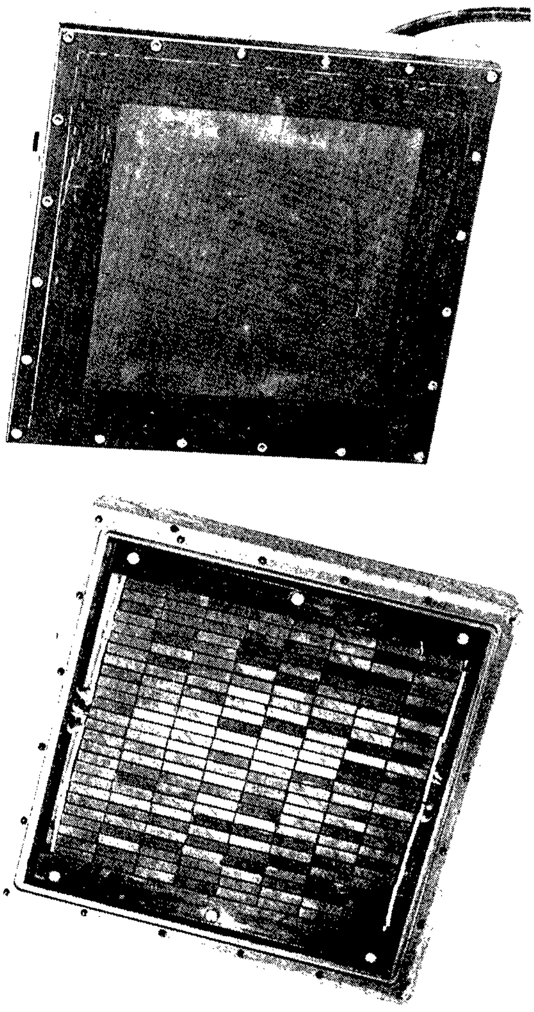


FIGURE 1. Typical early transducer.

The ratio of reactance to resistance (Q) even at resonance was so high that only a very narrow bandwidth could be achieved unless the transducer was badly mismatched to a high-powered amplifier.

The temperature dependence of 45-degree X-cut Rochelle salt crystals in these early transducers rendered them incapable of radiating the desired acoustic power. Most of them dropped 20 to 40 db under the ideal 110 db above 1 dyne per sq cm at 1 yd.

Because of variations of efficiency among the crystals in any given array, the directivity patterns were frequently unacceptable.

In some models the backing plate exhibited a mode of flexual vibration in the band of operating frequencies. This vibration superimposed on the crystal vibration gave such odd configurations to the directivity patterns that the units were unusable.

In some instances transducer behavior exhibited time-dependence which was thought to arise from changes occurring in the glued joints between crystals and backing plates under operating conditions, particularly after a period of high-power operation.

Because of all these defects and others of minor but annoying nature the frequency response of many of these early models was too irregular, undependable, and unpredictable for use with FM systems.

Loss of efficiency at the joint of the crystal and backing plate proved a serious problem in the early transducers. A study of cementing procedures and a careful control of temperature and humidity have led to joints whose losses are no longer an important factor.

A less easily apprehended cause of transducer inefficiency, and one which was not understood during the early stages of the development, is the viscous shear wave loss occurring in the castor oil which serves as a coupling medium between the acoustic window of the soundhead and the crystal faces themselves. This viscous shear wave loss arises from the tangential components of the motions of the crystals. If a crystal surface vibrates tangentially in a viscous fluid, shear waves are propagated from that surface. In castor oil (and similar fluids) the attenuation is very high at supersonic frequencies. The waves virtually vanish in the distance of a few millimeters. The energy so consumed contributes to the inefficiency of a transducer. For a single crystal isolated in an infinite ocean of castor oil the vis-

cous loss would be an unimportant factor. However, if a stationary surface or one undergoing different tangential motion is brought to within a shear wavelength of the vibrating surface the viscous loss increases very rapidly. Thus, a pair of crystals very close to each other and vibrating out-of-phase in an infinite ocean of oil would suffer very large losses. If the crystals were then separated a centimeter or so, allowing distance for the shear waves to attenuate, each would act virtually as if it were alone in the oil and the viscous losses would be greatly reduced. As this phenomenon became understood many previously obscure effects were explained. Improvement in transducers was achieved through designs which by arrangement of crystals in their relations to each other within the array tended to eliminate the loss arising from shear waves in the oil medium.

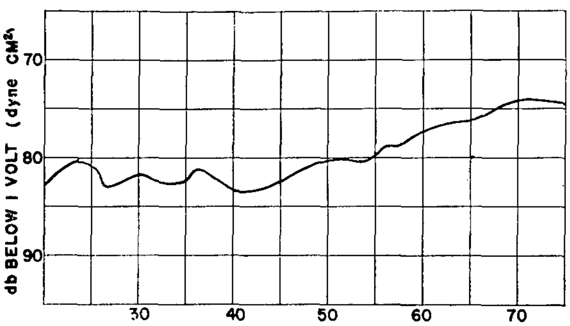


FIGURE 2. Frequency response of GA2-5 transducer (used as a hydrophone) measured at the end of a 32-ft cable.

6.3.1 GA2 Transducer

Typical of the transducers being constructed and used during the period of the development reported in the preceding discussion is the UCDWR unit designated GA2. The exterior case, backing plate, and acoustic window were of a standardized type intended primarily to facilitate rapid delivery of experimental units. No claim was made that the mechanical structure or the acoustic design were best suited to the needs of FM systems.

The GA2 contains 224 45-degree Y-cut Rochelle salt crystals each 3/8 in. by 1 in. by 1/4 in. in a rectangular array (8 7/32 in. by 7 27/32 in. consisting of 28 rows, eight crystals in a row). The crystals are separated by 1/32 in. of Corprene and the entire array cemented to a backing plate of cast Meehanite, 9 in. by 9 in. by 1/2 in. One face of the Meehanite backing plate is coated with vitreous enamel to a thickness of 1/32 in. This layer of porcelain is ground flat and the crystals cemented to it. The crystals are connected in phase, all in parallel (no lobe suppression). The crystal motor is mounted in Corprene in a square-cast Meehanite case whose external dimensions excluding mounting bosses, etc., are 10 9/16 in. by 10 9/16 in. by 1 3/4 in. The case is closed by a square window made of rubber exhibiting the same sound conductivity coefficient (ρ-c) as water. This window is 1/2 in. thick and the open area covered by the window is 8 in. by 8 in. The entire case is filled with castor oil. The overall dimensions of the soundhead are 10 9/16 in. by 10 9/16 in. by 3 1/2 in.

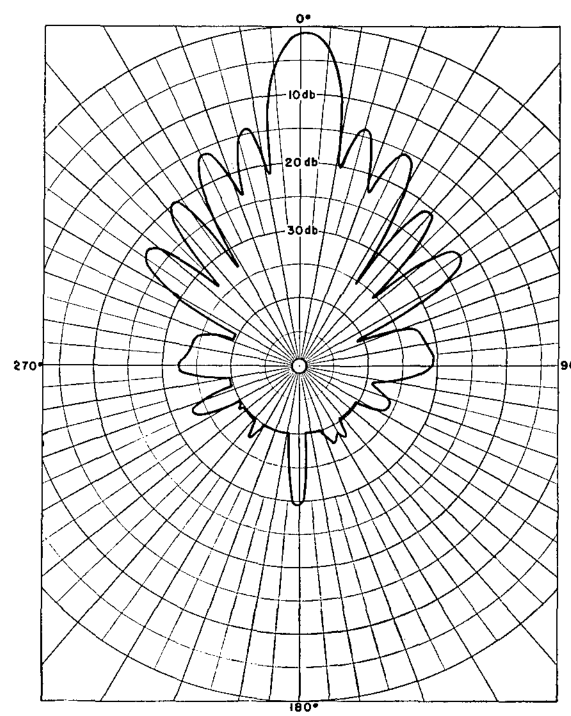


FIGURE 3. Directivity pattern of a GA2-5 transducer (used as a hydrophone) measured at 42 kc in a plane perpendicular to the radiating face at its center and parallel to the side.

The first GA2 transducer was built in January 1943 and a subsequent unit GA2-5 was

constructed in April 1944, for use with an FM system.

This transducer was designed to resonate near 40 kc and to show an open-circuit voltage as a receiver at approximately 63 db below 1 volt for 1 dyne per sq cm normally incident. For actual response of this transducer as a receiver at the end of 32 ft of cable, see Figure 2. To obtain the open-circuit voltage of the transducer a correction must be made for the contribution of the cable. This correction would raise the curve a little less than 6 db. Thus at the highest point the transducer open-circuit voltage is only −68 db and this occurs near 70 kc. At 40 kc where resonance should occur the response is −77 db. While this transducer proved useful for research in which high efficiency was not required it is obvious that it fell far short of solving the transducer problem set up in the early portions of this chapter.

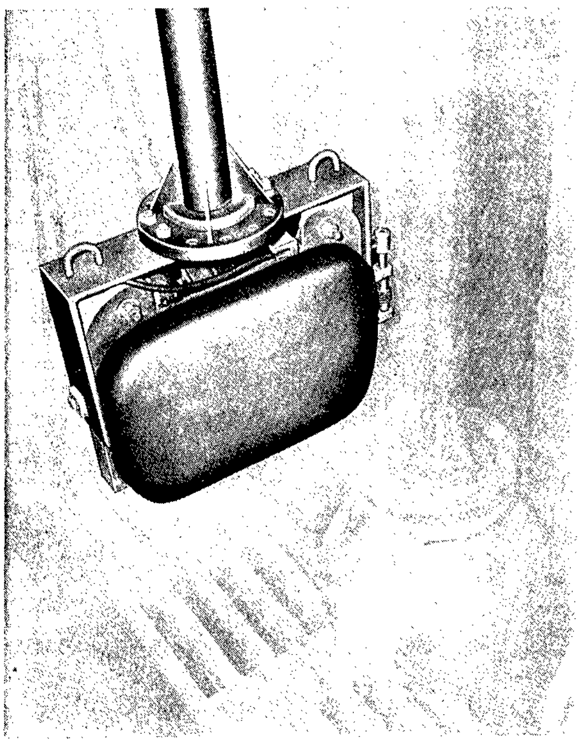


FIGURE 4. Supersonic prism of the Bell Telephone Laboratories.

Figure 3 gives a typical GA2 directivity pattern. While the pattern is reasonably symmetrical, side lobe suppression is far from ideal.

6.3.2 Bell Telephone Laboratories Supersonic Prism[22]

This transducer is described not only because it was typical of transducer construction at the time, but because it was the only transducer used for Pribar systems (modification of Cobar) and contained an elaborate phase shifting network.

The Bell Telephone Laboratories supersonic prism (see Figure 4) contains 504 45-degree Y-cut Rochelle salt crystals each 3 by 2½ by 0.625 cm. The foils are attached to the 3 by 2½-cm faces and the 2.5 by 0.625-cm faces are the radiating faces. The crystals are cemented together in groups of four, each block having a radiating face 2.5 cm by 2.5 cm. The blocks are arranged in 14 rows of 9 blocks per row to form a rectangular array 16⅓ in. by 9⅝ in. Each block of four is cemented to a ceramic wafer which in turn is cemented to a cast steel backing plate. The plate has 14 milled steel bars integral with the plate directly opposite the 14 rows of crystals. These bars are 2.340 in. thick measured from the front surface. This dimension of the bar is equivalent to one-quarter wavelength in steel near 20 kc.

A separate pair of terminals issues from each of the 14 crystal rows. When all these are connected in parallel, the transducer is uniformly driven (not lobe suppressed) moderately directional in the vertical plane and less so in the horizontal plane. The acoustic window is a big, rounded, rubber molding (rubber of the same sound conductivity coefficient as water) which fits around the edges of the backing plate and bulges out in front of the crystals. The rubber window is acoustically coupled to the crystals with castor oil. This description applies to the transducer proper.

An additional feature was embodied from which the name supersonic prism was derived. Any plane rectangular array of uniformly driven crystals has in planes parallel to its edges the directivity pattern of uniform line sources of the same length as the respective edges. Thus the maximum response is found on the normal to the center of the array and falls off symmetrically on the two sides (the side lobes, etc.). If electric networks are interposed

to produce a uniform phase shift proportional to distance across one direction of the array, the maximum response will be steered through an angle proportional to the phase shift per unit of length. Note that the steering angle in degrees is much less than the total phase angle in degrees.

A secondary result of such steering is that the main lobe and side lobes are broadened somewhat but if the steering is less than ± 45 degrees this effect is negligible. The effect of the phase steering is quite similar to a simple mechanical rotation of the array.

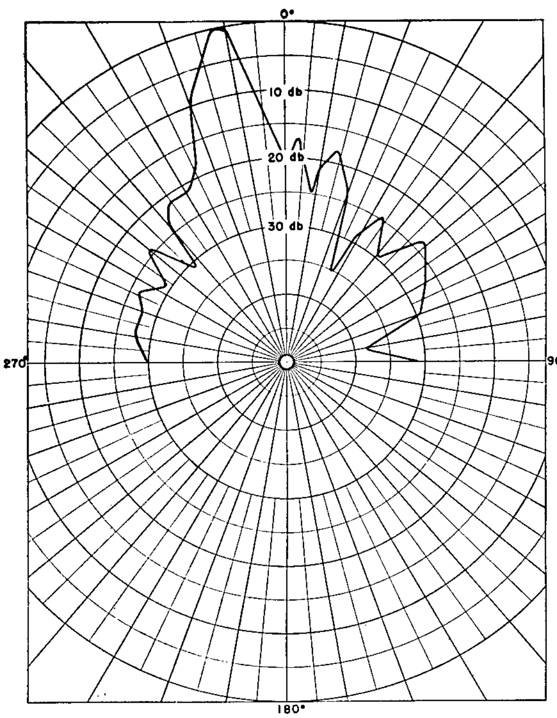


FIGURE 5. Directivity pattern of the supersonic prism (used as a hydrophone) taken at 19.8 kc in a plane parallel to the long axis and normal to the crystal array.

With the supersonic prism a confluent band-pass filter is used to obtain this steering. The filter has 13 sections each connected between rows of crystals, and the shunt electrical capacity of the crystals is made a part of each filter section. As energy passes through this filter it is tapped off to the successive crystal rows, so that the filter impedance is tapered to distribute the energy uniformly across the crystal array. The filter is terminated in its characteristic impedance to prevent reflections. The phase shift of the filter is proportional to frequency; consequently, the angle by which the main lobe is steered may be expected to be proportional to frequency. As an input signal is raised from 18 to 24 kc the main lobe sweeps from one side to the other. The original calculations indicated that the steering should be from +90 degrees to −90 degrees as the frequency swept from 18 to 24 kc. The filter is enclosed in a box behind the crystal backing plate. Relays are provided by which the filter may be removed and all crystals connected in parallel. To protect the filter elements a cold cathode tube is provided which limits the input power to approximately 1 watt. When the filter is switched out this tube is also removed, and as much as 1 kw may be put into the transducer. The complete assembly weighs 550 lb and measures $28\frac{1}{4}$ in. by $25\frac{1}{2}$ in. by $14\frac{1}{2}$ in. excluding mounting details.

The transducer was intended for the frequency band extending from 18 to 24 kc. As used with Pribar systems, its longest axis was in the horizontal plane.

The resonance occurs at $20\frac{1}{2}$ kc as designed, but the resistive term of the complex impedance is virtually the same in air as in water which would tend to indicate that the efficiency is only moderately good. From a typical directivity pattern as shown in Figure 5, it is evident that steering is accomplished. However, the steering is not available over as wide an arc as had been expected, perhaps because the capacity of the crystals is a function of frequency near resonance; and also probably because of small variations among the components. Side lobes are rather irregular, and are only 10 to 15 db down at the various frequencies. Use of the Bell Telephone Laboratories' supersonic prism as a transducer with an FM system proved the possibility of phase steering.

At this point in the program development of transducers as projectors and hydrophones began to proceed along divergent lines. Accordingly, the following reporting is covered under these two separate headings.

6.3.3 Projector Development

One of the first units to be designed specifically as a projector was designated the CP1-1.

It contained 1,080 X-cut Rochelle salt crystals $1\frac{1}{2}$ in. by 1 in. by $\frac{1}{4}$ in., so arranged as to form a cylindrical radiating surface $13\frac{1}{2}$ in. in diameter and $15\frac{1}{2}$ in. high. The 1-in. crystal dimension was the radiating dimension and the $1\frac{1}{2}$-in. dimension was parallel to the cylinder axis. The assembly consisted of 36 independent

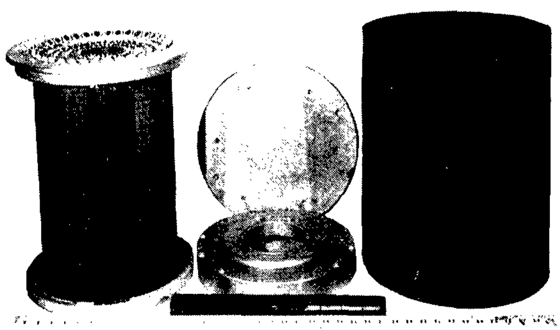


FIGURE 6. CP1-1 projector disassembled.

crystal motors arranged around a hollow steel core. Each motor contained 30 crystals and was split in the middle for vertical BDI. Each motor was surrounded on five sides by Corprene to which the crystals were cemented. Sep-

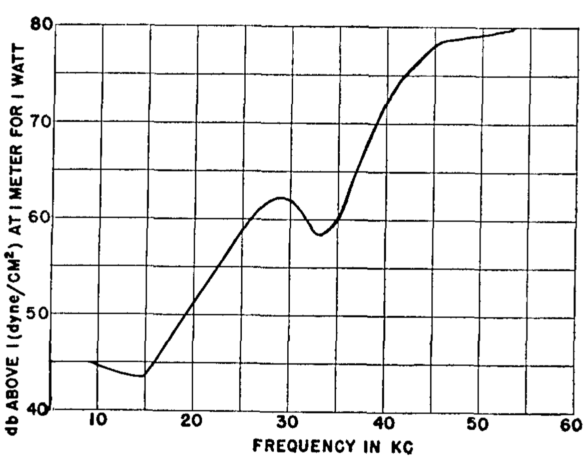


FIGURE 7. Frequency response of CP1-1 for 1-watt input.

arate terminals were brought up for each half of each motor so that any combination of the 36 motors could be used with or without BDI. The transducer was contained in a cylinder 15 in. OD by $1\frac{1}{8}$ in. thick and the remaining space was filled with castor oil. Various components of this projector are illustrated in Figure 6.

The projector had been designed to resonate at either 14 kc or 22 kc. Reference to Figure 7 shows that this specification is not met. It had been hoped that the projector would radiate roughly 110 db above 1 dyne per sq cm to 1 yd. Figure 7 shows that at 22 kc the transducer delivered only 67 db above 1 dyne per sq cm at 1 yd for 1-watt input. Thus, to deliver 110 db would require 20,000 watts of power which was a manifest impracticability. At 14 kc the situation was even worse.

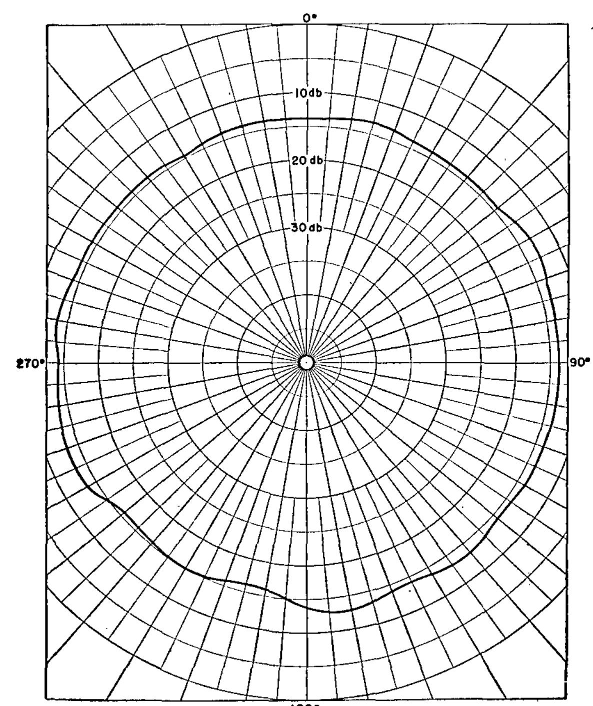


FIGURE 8. Directivity pattern of CP1-1 (used as a hydrophone) measured at 20 kc in a plane perpendicularly bisecting the axis of symmetry. All crystal banks connected.

A typical directivity pattern is shown in Figure 8, in which all 36 crystal motors are connected in parallel.

CP SERIES OF PROJECTORS

Following the failure of the CP1-1 to deliver power as hoped, a series of projectors designated by other CP numbers was developed. Each varied slightly from its predecessor in the

width of the angle of the projected beam and selection of radiating face of the crystal. One of the series utilized 45-degree Y-cut RS crystals in an effort to achieve better temperature stability. Some of these units gave a better frequency response pattern in the desired band than had the CP1-1, but none of them were efficient enough to produce the desired power in the water.

It was discovered during this experimentation that a most probable reason for the inefficiency of these transducers was the fact that the crystals had been imbedded in a Corprene mat. This technique had been adopted because of the difficulty experienced in cementing the crystals to the backing plate properly by any other method then known. A unit known as CP7 was constructed in which 45-degree X-cut Rochelle salt crystals were cemented to slender steel bars arranged like barrel staves around a hollow core. A curved backing plate was not used because the flexural modes of vibration of curved backing plates were not completely understood.

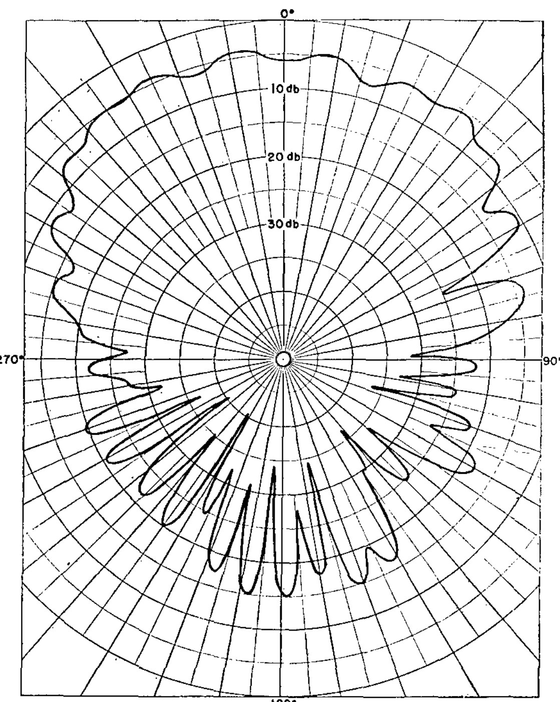


FIGURE 9. Directivity pattern of CP7-1 (used as a hydrophone) measured at 45 kc in a plane perpendicularly bisecting the long axis.

Directivity pattern of CP7-1 is illustrated in Figure 9. At 27 kc a deep notch developed in the forward direction (Figure 10). This notch caused the corresponding dip in the frequency response curve measured in this direction (Figure 11). The troublesome dip appeared and vanished smoothly as the frequency was varied throughout the band. Since the patterns were smooth and symmetric, it was assumed that the

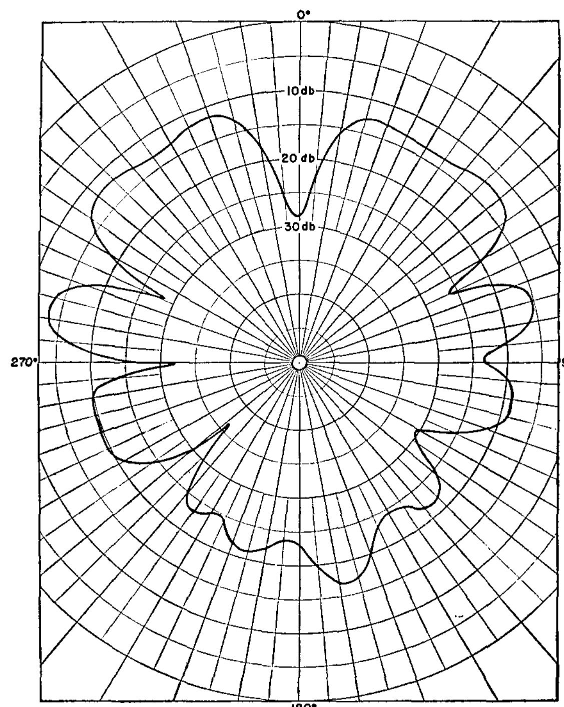


FIGURE 10. Directivity pattern of CP7-1 (used as a hydrophone) measured at 27 kc in a plane perpendicularly bisecting the long axis.

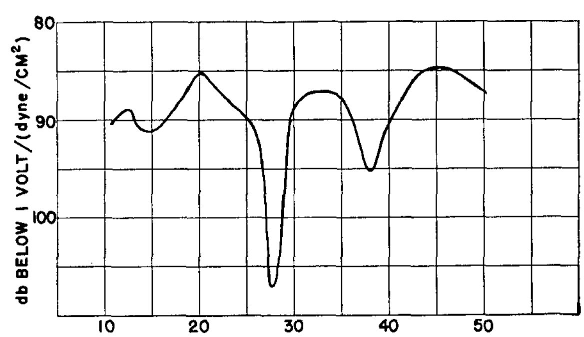


FIGURE 11. Frequency response of CP7-1 (used as a hydrophone) measured at the end of a 30-ft cable.

troublesome notch was traceable to the particular arrangement of the bars which had been used instead of a curved backing plate. Sound output was 80 db above 1 dyne per sq cm at 1 yd falling considerably below the desired 110 db. Experiments being conducted concurrently with other CP units indicated that the 45-degree X-cut Rochelle salt crystals might be in part responsible for the inefficiency of the unit.

Accordingly, the CP8-1 was constructed employing 45-degree Y-cut Rochelle salt crystals

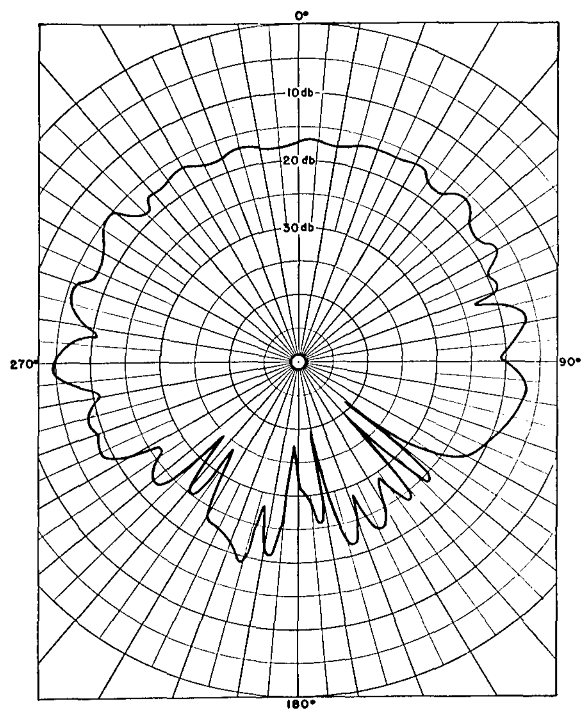


FIGURE 12. Directivity pattern of CP8-1 (used as a projector) measured at 35 kc in a plane perpendicularly bisecting the long axis.

0.710 in. by 0.465 in. by 0.25 in. The 2,340 crystals were arranged on 39 bars in a projector which covered 240 degrees in the horizontal plane. As in previous CP units the crystal array was contained in an oil-filled Neoprene cylinder.

The directivity pattern filled a 240-degree angular beam throughout the band from 30 to 39 kc as illustrated in Figure 12. Outside this frequency band there were other frequencies at which the patterns broke up into spoked designs showing deep notches between the lobes (Figure 13).

The response curves (Figure 14) were not suitably flat and varied about 11 db over the band from 30 to 39 kc (a 30- to 39-kc band was

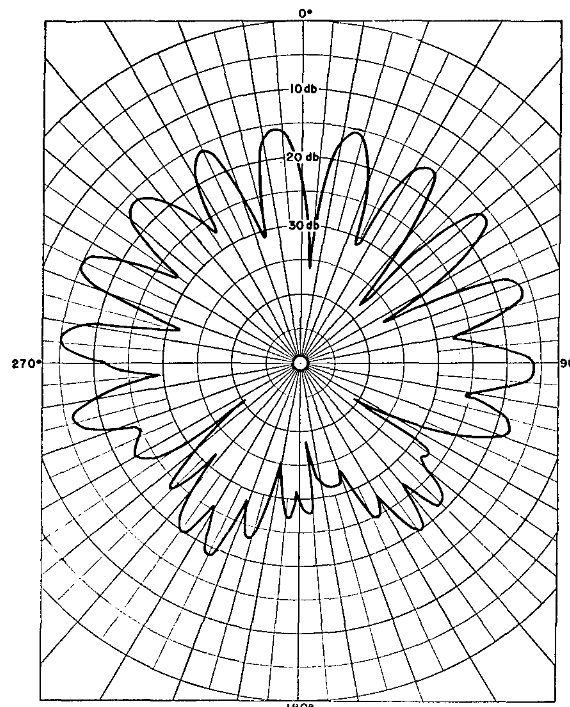


FIGURE 13. Directivity pattern of CP8-1 (used as a projector) measured at 29.95 kc in a plane perpendicularly bisecting the long axis.

being tried out in the FM system for which CP8 was intended). The CP8 was able to de-

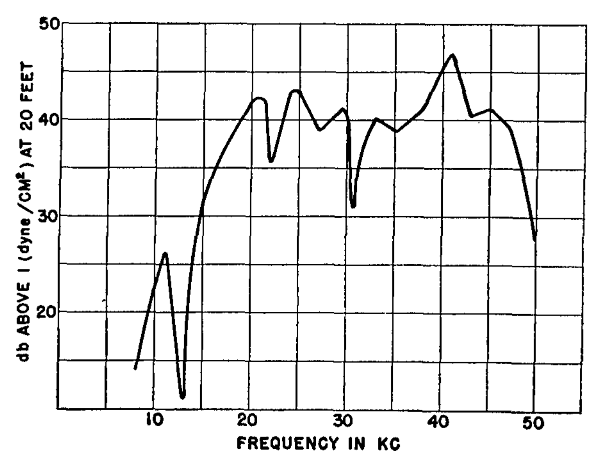


FIGURE 14. Frequency response of CP8-1 (used as a projector) measured with a constant 10-ma input to the end of a 28.5-ft cable.

liver between 90 and 100 db above 1 dyne per sq cm at 1 m which was an improvement over

previous projectors but still 10 to 20 db below the desired 110-db level. The use of 45-degree Y-cut Rochelle salt crystals and better technique of cementing them to porcelainized steel bars as a backing plate appeared to account in general for the improvement which had been made.

Further investigation gave a clue to the low efficiency of the CP8. It was found in the design

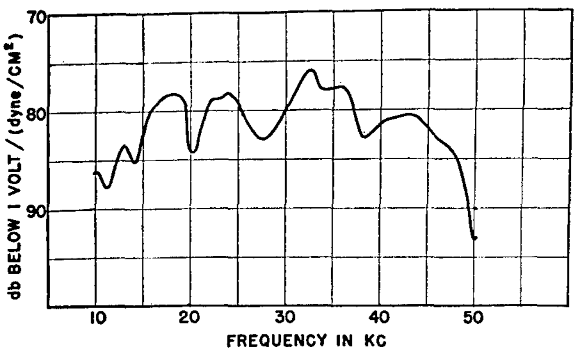


FIGURE 15. Frequency response of CP10-1 (used as a hydrophone) measured at the end of a 40-ft cable.

of large flat arrays that crystals operate better when separated into small groups. If a large number of crystals are packed closely so that each one is touching its neighbor, the efficiency is almost always poor, whether the crystals are cemented together or not. The reasons for this are not thoroughly understood but the phenomenon can probably be explained by the fact that the crystals near the outer limits of the array must move laterally as the inner crystals expand and contract (maintaining constant volume, of course). Since all crystals are in phase, the effect is cumulative and becomes more noticeable as it progresses from the center toward the outer limits of the array. This lateral motion gives rise to serious shear losses in even a good cement joint between crystals and backing plate.

The crystals in CP7-1 and CP8-1 had been so arranged on the bars that the direction parallel to the length of the bar was normal to the electrode face of the crystals and hence little shear loss should have been encountered, since first order theory indicates that crystals do not vibrate appreciably in a direction normal to their electrode faces. In spite of this a unit designated CP10-1 was constructed in which the crystals were spaced in small groups along the length of the bar. CP10-1 employed 336 45-degree Y-cut Rochelle salt crystals each 0.710 in. by 0.465 in. by 0.25 in., arranged on 12 porcelainized steel bars to give a projected beam width of 90 degrees in the horizontal plant. The electrode faces of four crystals were cemented together to form a group 0.710 in. by 0.465 in. by 1 in., and seven such groups spaced $\frac{3}{16}$ in. apart were cemented along each bar. All crystals were in phase and the crystal motor itself was contained in the usual oil-filled Neoprene cylinder.

This unit showed an improvement in output and gave 6 to 10 db more above 1 dyne per sq cm at 1 yd than previous models. The response curves showed a noticeable resonance for the first time (Figure 15). The directivity patterns were much improved by a rearrangement of the backing plate bars which put the radiating crystal faces on a 6-in. radius of curvature.

While the maximum power output was somewhat improved, CP10-1 was unable to deliver 110 db above 1 dyne per sq cm at 1 yd.

At this point in the development ammonium dihydrogen phosphate [ADP] crystals became

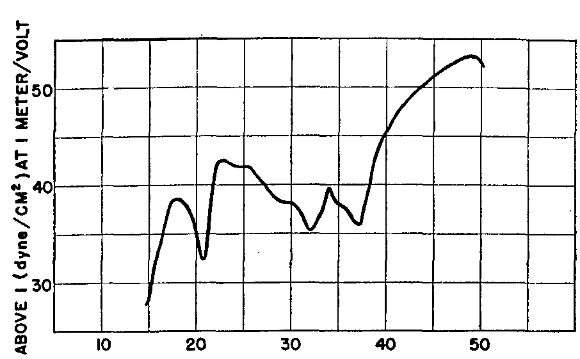


FIGURE 16. Frequency response of CP10Z-2 (used as a projector) measured with a constant 10-ma input to the end of the cable.

available and a model designated CP10Z-1 was constructed utilizing these new crystals (approximately 1 in. long) but differing very slightly in other respects from the CP10-1 just reported.

Early tests with the CP10Z-1 indicated that its resonance was low and out of the 36- to 48-kc

band which by that time was the standard band for FM systems operation. Accordingly, the crystals were milled down to 0.71-in. length to increase the resonant frequency of the projector to approximately 48 kc (Figure 16). With the change in resonant frequency the projector was redesignated CP10Z-2.

The CP10Z-2 proved capable of sound output up to 110 db above 1 dyne per sq cm at 1 m. The directivity patterns were smooth and fairly

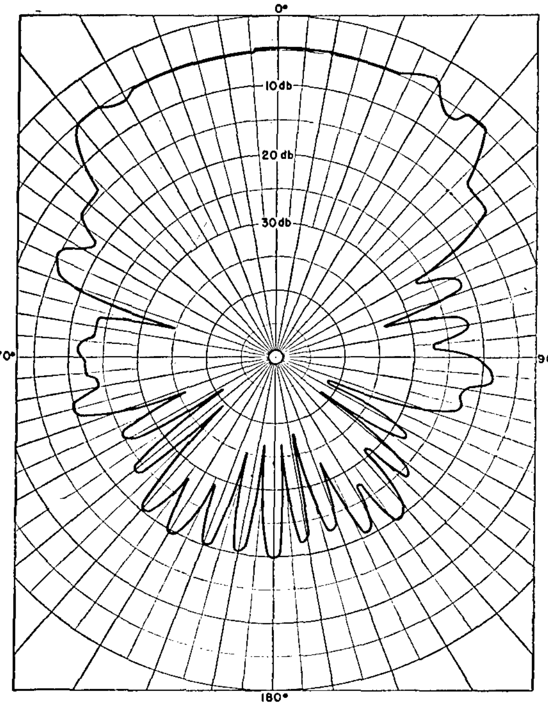


FIGURE 17. Directivity pattern of CP10Z-2 (used as a projector) measured at 43 kc in a plane perpendicularly bisecting the long axis.

symmetric and filled a 90-degree sector within about ± 3 db (Figure 17). In the vertical direction (Figure 18), the width of the main lobe was 13 degrees at 6 db down points. Such a configuration of the main lobe was acceptable for use with the FM systems at that time although the side lobes were considerably higher than what is considered to be ideal.

The CP10Z-2 type of projector together with a GA2 hydrophone saw service on FM installations in the Mediterranean area and on the submarine *Spadefish*. The historic nature of these installations was mentioned in Chapter 1.

6.3.4 Hydrophones

During the early stages of transducer development, experiments were conducted with a large assortment of hydrophones. Hydrophones designated as GA1, GB1, EB (used with the Fampas systems up to and including FM sonar Model 1, No. 1) GC2-1, GA2, etc., were used in combination with various projectors. Although these hydrophones differed in size, shape, and other noncritical details, they were similar from the transducer designer's standpoint.

All were plane arrays, usually square or circular, with the crystals cemented to a porcelainized steel backing plate, sometimes lobe suppressed, and contained in a cast-iron case with a plane parallel acoustic window. The effi-

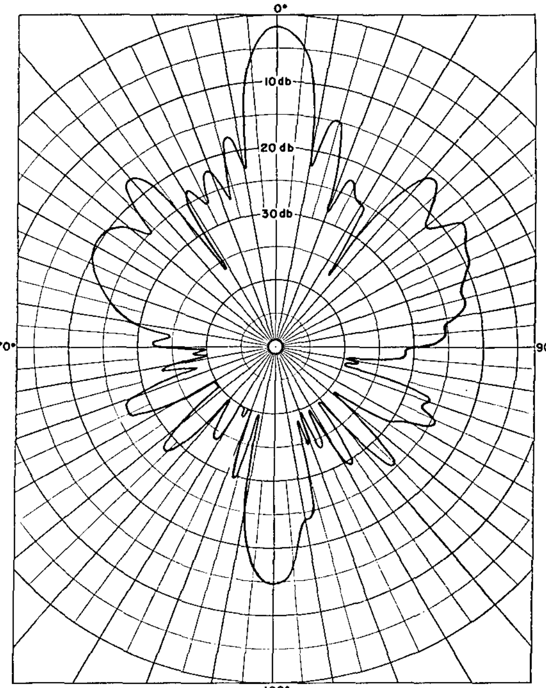


FIGURE 18. Directivity pattern of CP10Z-2 (used as a projector) measured at 40 kc in a plane perpendicularly bisecting the long axis.

ciency of these units was usually poor but not critical because of the amplification available in the FM system's receiver. The worst feature of these early hydrophones arose from the lack of sufficient lobe suppression. The GA2 hydrophone is representative of this group. For re-

sponse data and directivity patterns see Figures 2 and 3. While the lobe suppression appears to be close to the theoretical value for a uniformly driven square array, tests during this early period developed the fact that for use with FM systems an increase in lobe suppression by at least 10 db would be helpful.

In an attempt to achieve better lobe suppression a hydrophone designated GA14Z-1 was constructed, employing a circular array (mounted on a square backing plate) and using an annulus driven at one-third the amplitude of the central disk. The inside diameter of the annulus (and diameter of the central disk) was 0.61 per cent of the outer diameter of the annulus. The hydrophone comprised 408 45-degree Z-cut ADP crystals each 0.800 in. by 0.50 in. by 0.25 in., cemented together in triplets with each triplet separated from its neighbors by about 1/8 in. The backing plate was 1/2-in. thick cast Meehanite, about 10 in. square, covered by porcelain enamel. In other respects the unit was similar to GA2.

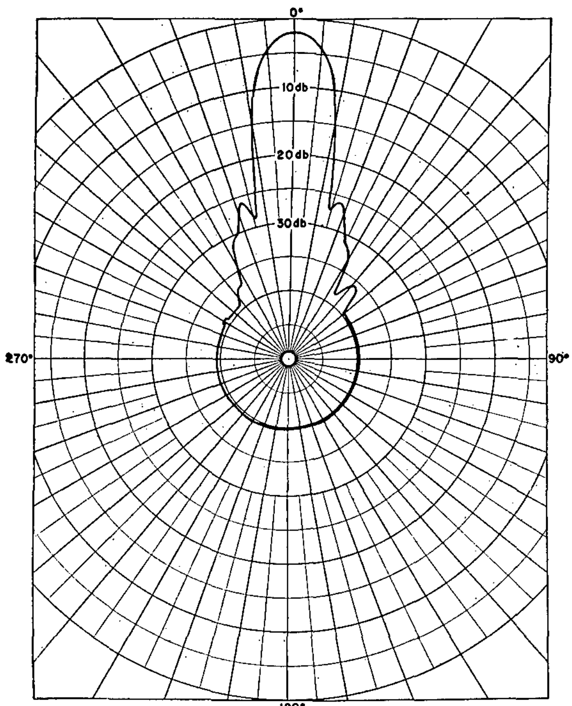


FIGURE 19. Directivity pattern of GA14Z-1 (used as a hydrophone) measured at 46 kc in a plane perpendicular to the crystal array at its center.

Theoretically, such an arrangement should give a first (and most intense) side lobe 27 db down from the main lobe. Such suppression would be 10 db better than that in the GA2 and similar hydrophones. Actual directivity measurements made on GA14Z-1 (see directivity pattern in Figure 19) indicated that at some frequencies the actual lobe suppression was even better than theoretical and that at no frequency was the suppression poorer than −26 db. The array, 9 in. in diameter, had a main lobe whose width was about 15 degrees at the 6-db down points and corresponded with the then current doctrine on hydrophones for FM systems.

The hydrophone response (Figure 20) shows a marked resonance near 45 kc where the response is only a few decibels below the theoretical maximum. A study of the response curve over the FM operating band of 36 to 48 kc, however, shows low values in the range between 36 and 43 kc. An attempt was made to cure this poor response in the lower portion of the operating band by lowering the resonant frequency by means of reducing the length of the crystals from 0.800 in. to 0.700 in. and increasing the thickness of the backing plate from 1/2 in. to 3/4 in. The unit embodying these modifications was designated GA14Z-2 and was otherwise identical with GA14Z-1.

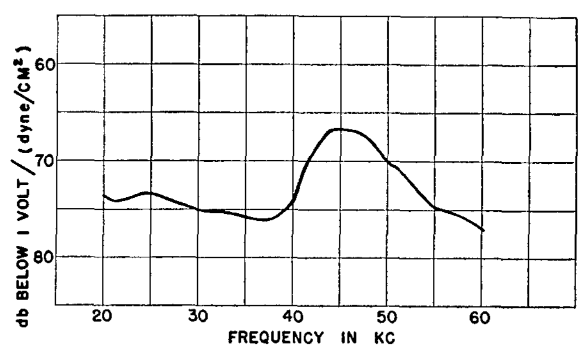


FIGURE 20. Frequency response of GA14Z-1 (used as a hydrophone) measured at the end of a 40-in. cable.

GA14Z-2, and subsequent transducers built on the same general pattern and designated by different model numbers to represent minor changes, did not come up to expectation. Directivity patterns and peak response in these

various hydrophones remained relatively good (see Figures 21 and 22 for typical curves), but the resonant frequency appeared not to be lowered by the various changes. A theory was advanced that the resonant frequency had perhaps actually been lowered, but that some fault (at that time not known) in the design or construction caused the hydrophones to exhibit in-

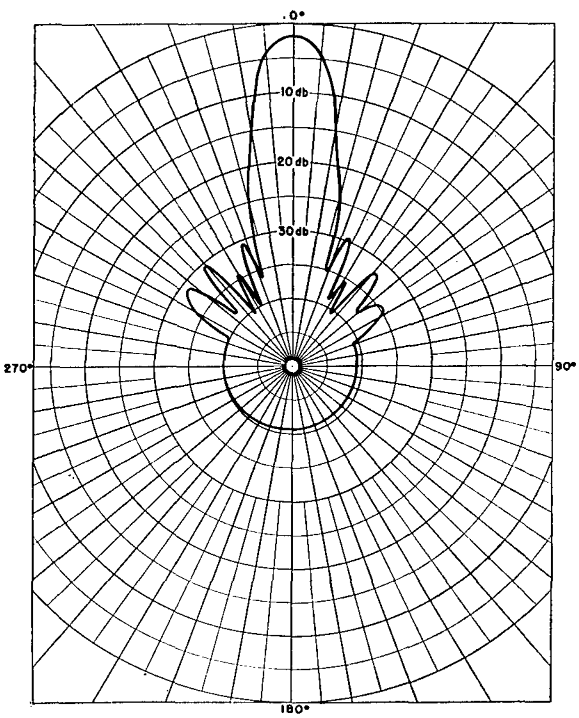


FIGURE 21. Directivity pattern of GA14Z-3 (used as a hydrophone) measured at 46 kc in a plane perpendicular to the crystal array at its center.

efficiency at frequencies lower than 43 kc. An explanation of the difficulty was finally found and is discussed later in connection with the CQ4Z transducers.

The GA14Z-2 and similar subsequent models were the best then available and accordingly a number of them were constructed and used with CP10Z projectors to form a transducer assembly for several early FM sonars [XQLA's]. Although the GA14Z-2 was the best hydrophone then available from an acoustic standpoint, it was mechanically crude and little attempt had been made at streamlining its housing.

In considering the possibility of improving the streamlining of the hydrophone, it was decided to investigate the matter of combining both projector and hydrophone in a single streamline housing. Accordingly, the transducers discussed from here on are treated as projector-hydrophone combinations.

6.3.5 Combination Transducers

CQ2Z-1

The first combination transducer comprised a CP10Z projector and a GA14Z hydrophone together with the tuning coil necessary for each housed in a common case. A 12½-in. diameter, 1-in. wall thickness, 36-in. high Neoprene tire stock cylinder mounted on a suitable steel framework enclosed both motors and the castor oil. Within the casing the projector was mounted above the hydrophone and the two were separated by a flat steel baffle which was intended to cut down crosstalk. Additional precautions against crosstalk took the form of a ⅛-in. foam Neoprene coating of the entire in-

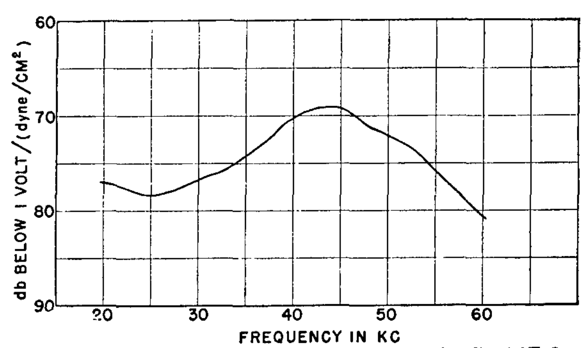


FIGURE 22. Frequency response of GA14Z-3 (used as a hydrophone) measured as open-circuit voltage.

terior of the sock except for the areas directly in front of the projector and hydrophone which served as acoustic windows.

Performance data of the CQ2Z-1 are given in Figures 23 and 24. In its simpler aspects, FM system performance depends upon the sum of the hydrophone and projector responses. It is evident that a sum curve combining hydrophone and projector responses would be peaked near the center of the 36- to 48-kc band and drop off rapidly toward the extremes of the band.

This peaked type of response-sum curve is undesirable in FM operation in that the gear is quite likely to detect targets only over a small portion of the frequency sawtooth if transducers having these characteristics are used. The ideal sum curve of hydrophone and projector responses, of course, would be relatively flat throughout the band.

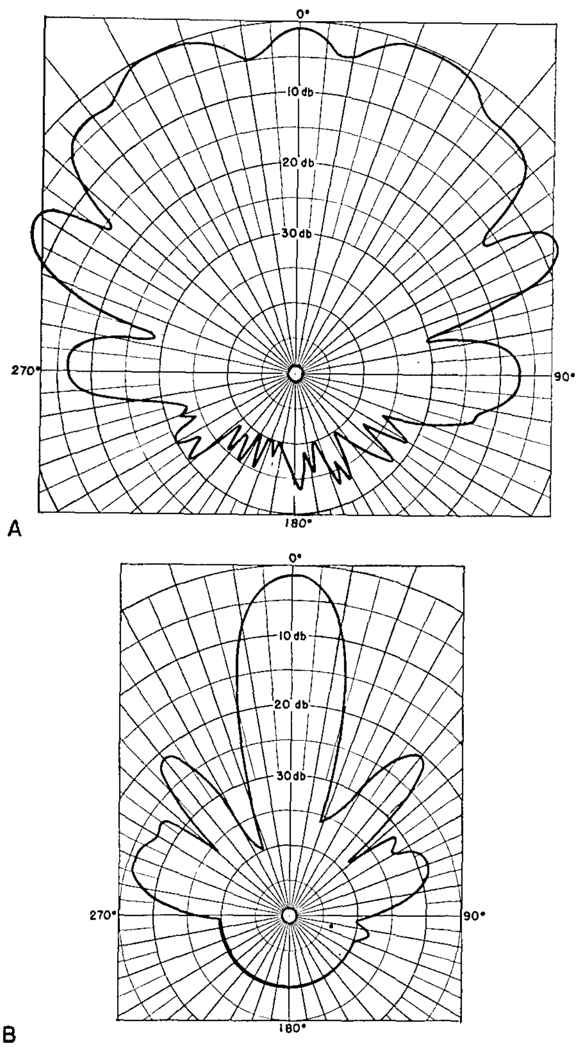


FIGURE 23. (A) Directivity pattern of CQ2Z-1, projector section, measured at 42 kc in a plane perpendicular to the long axis. (B) Directivity pattern of CQ2Z-1, hydrophone section, measured at 42 kc in a plane perpendicular to the long axis of the transducer.

The projector directivity pattern at 42 kc is fairly representative, but the notches at ±10 degrees become more marked at the upper end of the 36- to 48-kc band. Such notches cause the intensity with which a target is "illuminated" to vary several decibels as the transducer rotates.

The hydrophone directivity patterns illustrated in Figure 23 are typical. It will be noted that the excellent lobe suppression achieved in GA14Z has been lost by uniting the GA14Z hydrophone with a CP10Z projector in the CQ2Z combination transducer.

In spite of the fact that the sum curve of hydrophone and projector responses was not suitably flat throughout the operating band, and in spite of the fact that some lobe suppression had been lost in the combined unit, the CQ2Z represented a considerable mechanical improvement over previous hydrophone-projector combinations which had been separately housed even

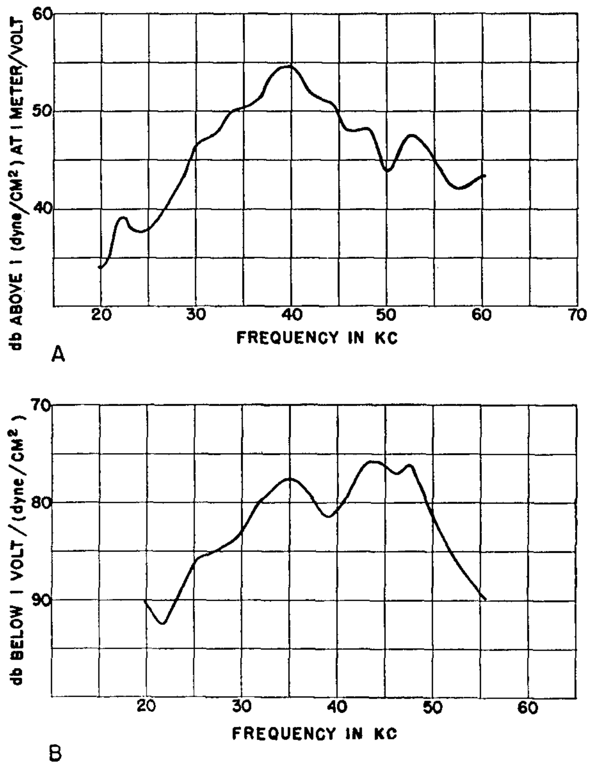


FIGURE 24. (A) Frequency response of CQ2Z-1, projector section, measured with a constant 10-ma input to the end of a 24-in. cable. (B) Frequency response of CQ2Z-1, hydrophone section, measured across a 600-ohm load (7.3 mh coil in series with each leg) at the end of a 24-in. cable.

though their separate housings were frequently bolted together during installations.

CQ4Z TRANSDUCERS

Because of the mechanical advantages inherent in the CQ2Z design a production prototype was brought out under the designation of CQ4Z which included certain refinements. Aside from trivial changes CQ4Z differed from CQ2Z in only three respects: (1) the overall height had been reduced from 36 in. to 32 in., (2) the sleeve had heavy steel rings molded into the ends of the rubber sock, and (3) the back half of the steel frame had added to it a curved ⅜-in. thick steel plate fitting just inside the rubber sleeve. The last two modifications were made in the interest of increasing the ruggedness of the unit. For topside submarine installation, it was recommended that the transducer be trained aft when not in use in order to present its reinforced back to the seas. The redesign also incorporated a further attempt to reduce crosstalk by coating a ¾-in. thick baffle between the hydrophone and projector with foam rubber on both of its faces. The crystal motors were also mounted in their brackets on foam rubber washers and bushings so that no metallic path existed by which sound could leak from projector to hydrophone.

The performance data on the CQ4Z did not differ greatly from that already shown for CQ2Z. A sum curve derived by combining the hydrophone-projector responses appeared perhaps a little better, and possibly the lobe suppression was not quite as great as in the CQ2Z. In essence, however, there was no important difference in the acoustic behavior of the transducers.

Actual production of CQ4Z transducers disclosed the fact that the performance of individual transducers did not adhere to a uniform standard. A long experimental program aimed at stabilizing this erratic performance resulted in insertion of small pieces of foam rubber between the crystal triplets on the receiver backing plate. Other small pieces of foam rubber were cemented to the sides of the crystal quadruplets along the projector bars. Tests made with the transducers modified in this manner indicated that the response curves were smoothed and production units began to behave uniformly when so treated. The reasons for the effectiveness of this modification are not thoroughly understood. It may be that the erratic performances of earlier models arose from the minute variations in the size and shape of the spaces between crystal groups, and in the quality of the glued joints by which the crystals were fastened to the bars.

CQ6Z

The CQ6Z was another production model utilizing the CP10Z projector and GA14Z hydrophone and embodying some minor changes to render the transducer more simple mechanically. The changes resulted in the elimination of approximately 100 parts in the design and permitting of easier fabrication by welding and copper brazing.

The mechanical changes made no important difference in its acoustic performance.

CQ8Z AND CJJ78256

With production units of CQ6Z considerable investigation was made into the problems of reducing crosstalk and improving the response and directivity patterns of the unit.

Dropping off of response on either side of the resonant frequency which is by design centered in the operating band is a disadvantage in FM systems operation, but is apparently inherently characteristic of crystal transducers. At 36 and 48 kc a sum curve of the projector and hydrophone responses shows a drop of roughly 6 db from the level near the center of the band. Because this lack of flatness could be somewhat overcome by simple equalization in the receiver amplifier, efforts were concentrated on improving the directivity patterns and diminishing the crosstalk.

Directivity Patterns. Because the crystal motor of GA14Z had a very satisfactory directivity pattern and the same motor was incorporated as the hydrophone in all CQ transducers, it appeared that the unsatisfactory directivity pattern in the CQ transducers arose from some fault in the transducer structure. The most likely cause of hydrophone pattern distortion appeared to be the Neoprene sleeve since no other element of the transducer struc-

ture appeared to be sufficiently near the crystal motor of the hydrophone to be acoustically coupled to it. This point of view was reinforced by the fact that the hydrophone patterns in the vertical plane were different from those in the horizontal plane although the crystal motor itself was circularly symmetric. The asymmetry of the directivity patterns, therefore, was thought to arise from the fact that the cylindrical rubber sleeve, and perhaps the two steel disks above and below the hydrophone, acted as mirrors. These effects were thought to distort the projector patterns though perhaps by not so great an amount as they did the hydrophone patterns. If the hydrophone patterns were in truth distorted by the rubber sleeve, then the sleeve could not be a perfect acoustic window. In this event the sleeve must reflect back into the interior of the transducer some portion of the energy radiated by the projector. Such a reflection would give rise to standing waves which could cause uneven frequency response and might also explain variations from unit to unit.

In view of the theory and empirical results set forth above, the next step was to procure a rubber sleeve for housing the transducer which would have the same ρ-c (sound transmission coefficient) constant as water.

Tests of a transducer equipped with a ρ-c rubber sock showed hydrophone patterns which had returned to the values obtainable with GA14Z when used alone as a hydrophone. The projector patterns were also noticeably improved. Response curves of both projector and hydrophone smoothed out to some extent.

Crosstalk. Investigations of the CQ6Z transducer utilizing the Neoprene rubber sock indicated that while the energy reflected back to the interior of the transducer probably caused very slight loss of radiated energy (about 1 or 2 db), nevertheless such returned energy raised the average internal energy density considerably. This effect would greatly increase the crosstalk level within the transducer between projector and hydrophone. The testing of a unit utilizing a ρ-c rubber sock proved this to be true and the crosstalk level dropped materially.

The crosstalk level, however, was still above what was considered acceptable for the FM system. Accordingly, further investigations were undertaken in an attempt to reduce the level of the crosstalk.

By pulsing the projector it was possible to measure the transit time of crosstalk from projector to hydrophone. Such measurements proved that the loudest crosstalk components all occurred after very short transit intervals, corresponding to total path lengths in water of only 1 or 2 ft (even less in steel). Such short transit time for major components of the total crosstalk indicated that the paths were probably through the structure of the transducer itself. Transit time over such paths even within the transducer itself may be greatly influenced by the presence or absence of the ocean's radiation impedance. It was decided to investigate the crosstalk of units operated in air. Results of these investigations showed that the sound transmission coefficient of ρ-c rubber was not identical with that of water. A very slight difference allowed the ρ-c rubber to act as a wave guide connecting the transmitter and receiver. Exact form of the waves (Rayleigh, longitudinal, etc.) is not known, but the gross phenomenon has been demonstrated.

In an attempt to stop the ρ-c rubber sock from acting as a wave guide, new rubber socks were ordered in which a Corprene (cork-rubber compound) ring was molded into the rubber sock between the upper and lower halves and extending completely around the rubber sock circumference. The Corprene band offered a large impedance mismatch to any kind of wave traveling through the ρ-c rubber between projector and hydrophone. It resulted in the further reduction of crosstalk level. Additional tests indicated that the residual crosstalk arose in the water (rather than in the structure of the transducer) and was caused by scatterers, surfaces, etc., in short, by reverberation. This appeared to pose an irreducible minimum to possible crosstalk reduction unless the two crystal motors (projector and hydrophone) were separated by relatively great distances. Accordingly, further efforts to eliminate crosstalk within the transducer itself were halted. Transducers incorporating the results of the research on directivity patterns and crosstalk, reported in the preceding paragraphs, were des-

ignated CQ8Z. Because the ρ-c rubber was not as sturdy as Neoprene tire stock it was decided to use a window only 180-degrees wide instead of a full cylinder of the rubber in order to obtain the support of a steel shell over the remaining 180 degrees. Because the method of constructing such a housing involved bonding the rubber permanently to the steel framework (no longer permitting easy access to the crystal motors by removing the rubber sock) it necessitated a few design changes. The hydrophone and projector were mounted on a framework which could be inserted through the bottom of the housing in the manner of a replaceable cartridge. Positioning was achieved by the use

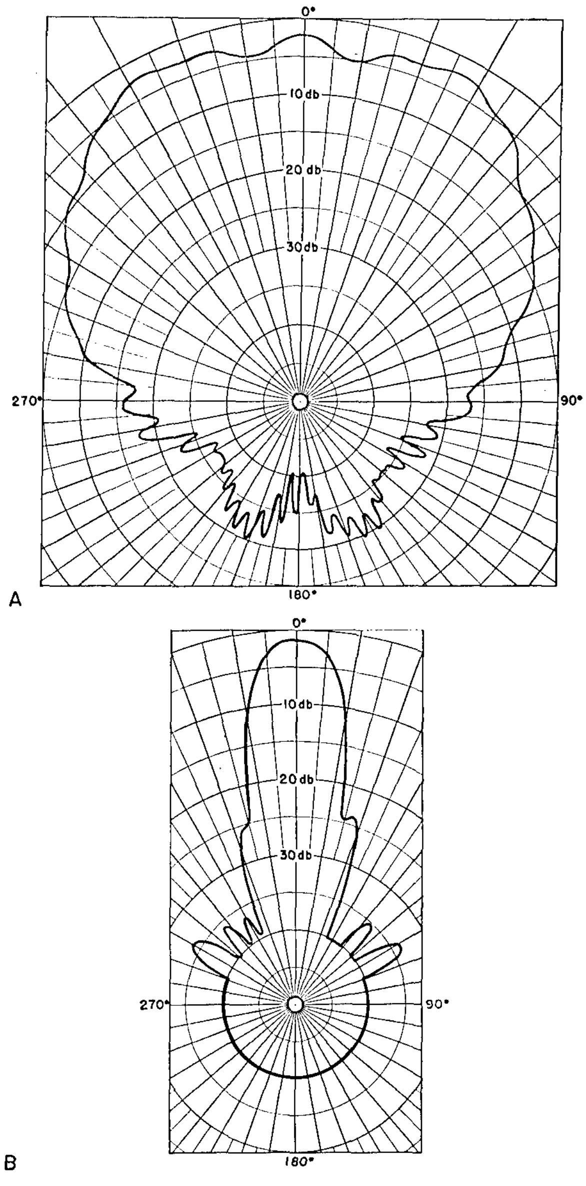


FIGURE 25. (A) Directivity pattern of CJJ-78256, projector section, measured at 42 kc in a plane perpendicular to the long axis. (B) Directivity pattern of CJJ78256, hydrophone section, measured at 42 kc in a plane perpendicular to the long axis of the transducer.

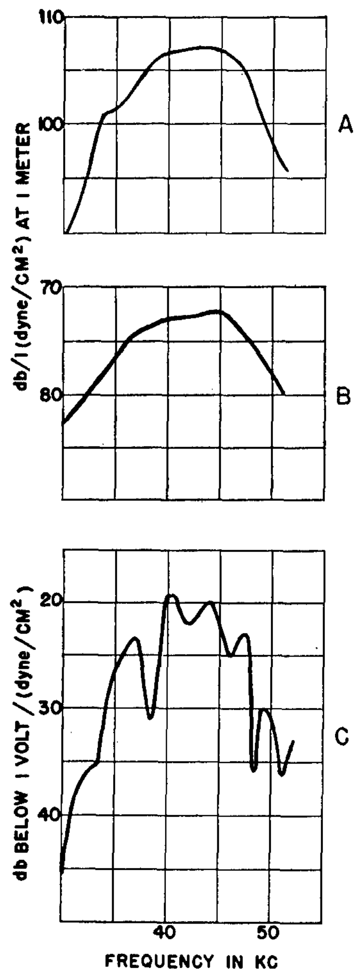


FIGURE 26. (A) Frequency response of CJJ-78256, projector section, measured while being driven by a QLA driver amplifier having a constant excitation of 6.8 volts. (B) Frequency response of CJJ78256, hydrophone section, measured across a 600-ohm terminal load at the end of a 23-ft cable. (C) Crosstalk of CJJ78256 measured as voltage across a 600-ohm terminal load at the end of the 23-ft hydrophone cable. The projector was driven by a QLA driver amplifier having a constant excitation of 6.8 volts.

of taper pins top and bottom, and once the cartridge had been inserted, the hole was made watertight by a circular bottom cover plate.

Because of the lack of strength in ρ-c rubber (compared to Neoprene tire stock) the thickness of the window was increased from 1 in. to 2 in. The Corprene ring was replaced by a steel semicircle bonded into the rubber at the equator between the upper and lower crystal motors. Other minor changes involved rearrangement of the foam rubber lining and acoustic isolation between hydrophone and projector. The CQ8Z used the same crystal motors as in preceding models; the CP10Z projector and the GA14Z used the hydrophone.

Results achieved with the CQ8Z resulted in its being put into production as soon as the design changes had been made. Before actual production had progressed very far the designation of the FM systems program was changed from FM sonar to QLA sonar and at the same time in keeping with the new nomenclature the CQ8Z transducer became known as a CJJ78256. Calibration data of a typical CJJ78256 transducer are shown in Figures 25 and 26. This is the transducer with which QLA-1 sonar is equipped.

6.4 TRANSDUCER THEORY AND FUTURE MODIFICATIONS

At the present writing it has been over a year since any attempt has been made to improve the crystal motors of transducers. During that time transducer art has advanced rapidly. Out of this advance in the art numerous suggestions for improvement in the transducer described as CJJ78256 suggest themselves.

Efficiency

Projector efficiency defined as the ratio of total acoustic power output at the driven frequency to electric power input at the driven frequency is the basic criterion for evaluating any transducer. Although other factors should be considered in the selection and design of a transducer, there is no question but that efficiency is the paramount concern.

The art of measurement of efficiency still leaves much to be desired, but various available methods when combined can fix the efficiency of a transducer roughly within ± 1 db if great care is taken in the measurements. Presumably the accuracy of measurement improves in time.

One cannot compare two transducers reasonably on the basis of pressure in the water for 1 volt applied nor upon open-circuit voltages for unit incident sound pressure. Such data ignore impedance. A fictitious improvement might be obtained simply by using thinner crystals in one case or thicker crystals in another.

Given a standard efficiency all transducers containing the same kind of crystals exhibit virtually identical characteristics (except in second order effects). Bandwidths, Q's, etc., are quantities inherent in the crystals and the only differences arise from size of array.

Other criteria of transducers after the prime consideration of efficiency are: pressure in water for 1-watt electric input, uniformity of voltage response, directivity pattern, etc. It is now theoretically possible to build efficient transducers having any reasonable directivity pattern and responses as high and as broad as the crystals themselves permit.

Projectors

The CJJ78256 used with QLA-1 sonar delivers at its best frequency roughly 110 db above 1 dyne per sq cm at 1 m with an efficiency estimated to be 50 per cent or greater. Tests indicate that the present unit could be driven at 6 to 10 db higher level if necessary.

Efficiency might be improved (by 1 or 2 db) by using inertia-driven, Cycle-Welded, ADP-rubber construction as developed by UCDWR. However, this method has not been explored fully and the maximum power radiation might be just about the present level of 110 db if the same number of crystals were used in the same kind of an array. Furthermore, such construction suffers unduly by low radiation impedance such as must result from spacing the crystals on a curve. The bandwidth might be no greater than at present.

Theoretically it should be possible to design an efficient ADP projector so that when driven by a regular system amplifier the pressure in the water would be down only 2 to 3 db at 36

and 48 kc as compared with the peak pressure at midband. This may never be achieved with ADP because of unavoidable inefficiency and reduced radiation impedance caused by the spaced array, but ADP is the best material now available.

The directivity pattern of the QLA-1 projector (see Figure 25) is almost identical with the theoretical pattern. The "bumps" arise from the spacing of the bars and (more important) from the incomplete arc (as compared with a full cylinder). The patterns would be improved by increasing the radius of curvature from the present 6 in. to approximately 8 in., and by packing the bars as closely together as possible. This would also raise the maximum power output about 1 db but would affect negligibly the pressure for 1-watt input (the only effect being an improvement in efficiency caused by improved radiation impedance).

Hydrophones

While the present hydrophone GA14Z serves fairly well with QLA-1 sonar and little attempt has been made to improve its design since it was established under the aforementioned designation, an improved hydrophone would be of considerable help to FM system operation in that so much gain would not be required in the receiver amplifier. With a more sensitive hydrophone and less gain in the receiver amplifier a certain component of internal set noise would be eliminated to the advantage of FM system operation.

Lobe suppression in the GA14Z hydrophone is achieved in two zones as previously described by an annulus driven at approximately one-third the amplitude of the circular disk which it surrounds. In order to produce a hydrophone whose lobe suppression is greater than —26 db it would be necessary to change the design to employ a large number of zones. The effectiveness of the complicated crystal patterns involved in lobe suppression by the use of a large number of zones is easily destroyed by tiny manufacturing irregularities.

The directivity patterns in the vertical plane for the hydrophone as well as the projector leave something to be desired. There is good reason to believe that the distortion encountered is caused by reflection from the upper and lower steel plates in the transducer itself rather than from some design in the crystal motors. Hence, any crystal motor would suffer a similar distortion unless a fundamental redesign of the structure of the entire transducer eliminated the plates.

Crosstalk

The crosstalk level in CJJ78256 is several decibels higher than the best experimental CQ6Z with Corprene-blocked ρ-c rubber sleeve. The performance of the CQ6Z in this respect was sacrificed as a result of engineering compromises. It could be recovered by the discovery of some new arrangement which would serve the same purpose as the Corprene band in a ρ-c sleeve of CQ6Z and also give the same structural strength that the steel band in the ρ-c window of the CJJ78256 offers.

Even the best possible isolation of projector from hydrophone within a single housing would leave some amount of crosstalk. One possible means of eliminating this crosstalk is to separate the projector (possibly a fixed 360-degree projector mounted topside) and the hydrophone (logically a rotatable hydrophone inside a fixed streamline ρ-c rubber "tear drop" dome, placed bottomside directly below the projector to eliminate parallax). Theory indicates that a QLA-1 hydrophone could be mounted in a heavy-walled, irregularly-shaped, ρ-c rubber "boot" without serious pattern distortion. Neoprene tire stock or metal domes (in spite of their structural strength) are entirely out of the question if a —26-db lobe suppression is to be retained at 36 to 48 kc.

Unit Construction

Navy Research Laboratory has recently developed a unit-type construction in which a crystal array is made up of a number of smaller assemblies each comprised of a small number of crystals attached to its own individual backing plate. The obvious advantages of this type of construction are (1) facilitates repair because faulty units may be replaced like vacuum tubes, (2) facilitates the construction of uniform transducers in that individual units may be selected for uniformity thus reducing greatly

the range of variations found in run-of-the-mine crystals, and (3) increases transducer efficiency and smooths frequency response because such small backing plates do not exhibit undesirable resonances in the operating band.

Such unit construction should be embodied in both the projector and hydrophone of future FM systems.

Chapter 7

ASSOCIATED DEVICES AND DEVELOPMENT

IN ADDITION to the particular directions of development which have been covered under the individual mark and model numbers, several other investigations were necessary to assist in proving or disproving certain phases of the FM investigation.

Discussion in this chapter concerns the resultant devices from these associated investigations. Certain of these associated devices were developed by the UCDWR, whereas others were developed and manufactured by outside activities. Each device is identified as to its origin and its relationship to the project as a whole.

7.1 UCDWR LIGHT VALVE

With the advent of multichannel FM systems, the need for a compact high-resolution acoustic

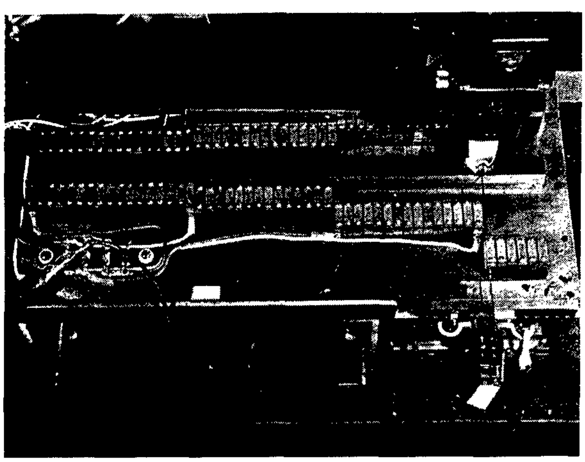


FIGURE 1. UCDWR light valve Model 1 (experimental) (100 channels—German silver).

analyzer became apparent. This need led to an extensive investigation of known methods of which the mechanically resonant light valve was one.

The arrangement of the UCDWR No. 1 light valve may be seen in Figures 1 and 2. In this unit a number of German-silver ribbons were tuned to slightly different frequencies in the spectrum to be analyzed. The ribbons were located in a permanent magnetic field and the audio-frequency currents passed through them causing vibration. When this vibration occurred at the mechanical resonance of one of the ribbons, the amplitude rose sufficiently to unmask a light which would fall on a fluorescent screen thus giving an indication of its presence.

Tests with the Model No. 1 light valve, although successful, showed the need for: (1) greater sensitivity, (2) the use of an electromagnetic field, (3) provision for external tuning, and (4) a more stable ribbon material less subject to overload.

The UCDWR Model No. 2 light valve, Figures 3, 4, and 5, was designed to include these features. Greater sensitivity was obtained by twisting the ribbons to reduce stiffness and to provide maximum hinging effect. The 60 ribbons for the respective channels were constructed of beryllium-copper for stability. Testing of the unit was discontinued due to marked improvement and bulk reduction of electronic and mechanical analyzers being developed concurrently.

7.2 ERPD MULTISTRING LIGHT VALVE[18]

The complex light valve completed by the Electrical Research Products Division of the Western Electric Company during 1944, operated on the same basic principle as the UCDWR unit.

One hundred metal ribbons were used to cover the audio-frequency spectrum from 500 to 2,975 c in increments of 25 c. Of necessity, since ribbon sensitivity varies with tuned frequency, transmission channels with controlled attenuation were provided to drive all ribbons to the same vibrational amplitude for a given signal level.

All signals in the audio spectrum to be analyzed passed through a preamplifier and then were divided by a network and filters into one of three bands, low frequency (less than 1,200 c), medium frequency (1,200 to 2,200 c),

and high frequency (above 2,200 c). Signals falling within each of the bands were suitably equalized or attenuated 6 db per octave for the low and medium and 10 db per octave for the high channel. These latter more sensitive ribbons were actually over-modulated but were provided with an ample safety factor to prevent breakage. The equalizers, then, had a transmission-versus-frequency curve nearly the inverse of the curve of sensitivity versus frequency for the associated section of the light valve.

Each of the three frequency-band circuits was provided with a limiting amplifier, attenuator, and power amplifier suitably isolated by pads in addition to the equalizers mentioned previously.

When a given ribbon was caused to resonate at its tuned frequency, the two immediately adjacent ribbons tuned to 25 c above and 25 c below respectively, responded with an amplitude approximately 6 db below the ribbon at resonance. This characteristic provided sharp definition at resonance and good resolution at frequencies occurring between the 25-c increments.

Damping of the valve ribbons to control Q was accomplished by shunting the ribbons together in groups which were then connected in series to form one of the three sections. The low-frequency section consisted of series-connected adjacent groups of four shunted ribbons; the medium-frequency section of three shunted ribbons; and the high-frequency section of two shunted ribbons. Thus within a group an excited ribbon was damped by the nonexcited ribbons which shunted it and con-

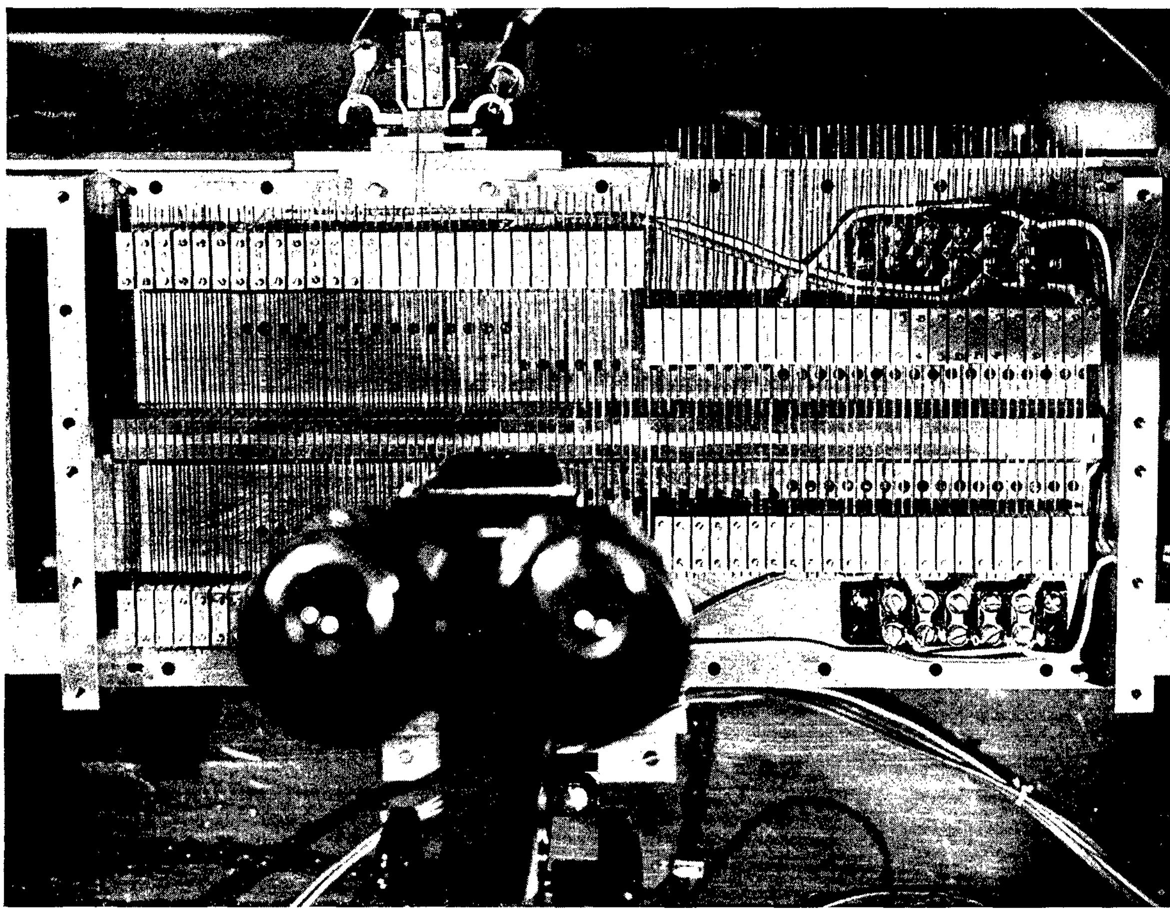


FIGURE 2. UCDWR light valve Model 1 (final form) (100 channels—German silver).

trolled Q to the desired value. Other nonactive groups functioned only as low-resistance connections in the section circuit.

The whole light valve and light source assembly were rotated in a 180-degree arc every 8 sec. An additional 10 degrees were provided for reversing direction (which was synchronized with the hydrophone) and microswitches limited rotation in cases of reversal failure. Two high-pressure mercury arc tubes (General Electric H-3 type) mounted in parabolic reflectors furnished the light source. The quartz burner tubes were air-cooled. Tuning frequency was held to ± 1 c by a sensitive thermostat operated in conjunction with the blower which held the valve temperature to 90 degrees $\pm 1°$ F.

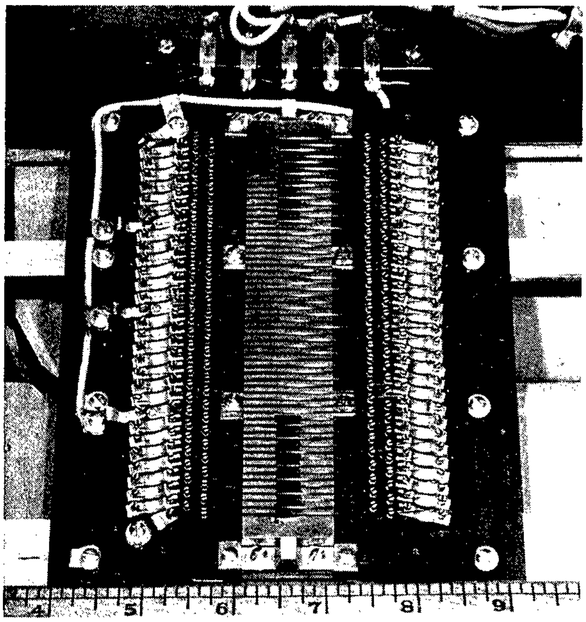


FIGURE 3. UCDWR light valve Model 2 (60 channels—beryllium copper).

7.2.1 Results

Underwater targets were accurately located at ranges up to 500 yd with the equipment. The target definition was good in spite of considerable water interference and the opening of several slots simultaneously.

Continuance of the project was abandoned since war demands made the compromise of the 20-channel electronic gear necessary from a volume production standpoint.

7.3 PPI (CHEMICAL) RECORDER

7.3.1 Introduction

The desirability of using a recorder with FM sonar was suggested early in 1944 when during evaluation tests it was necessary to plot the targets found in a certain area in accordance with the data obtained from the FM sonar. It was thought that a device of this type would be of great assistance in mapping areas where mines or other navigational hazards might be present. Consideration was first given to the modification of a standard Sangamo chemical recorder. After preliminary investigation it was decided that it would be more satisfactory to construct a completely new recorder. Design work began on this unit in April 1944.

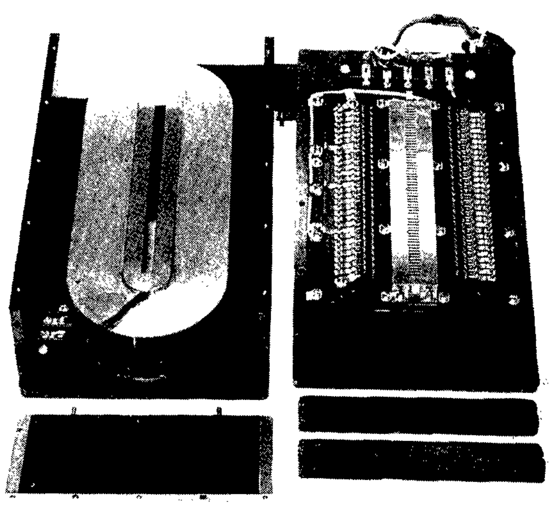


FIGURE 4. UCDWR light valve Model 2 partially assembled view. *Left*, electromagnet. *Right*, valve.

7.3.2 Construction Details

In the construction of this recorder a circular plate of insulating material (Micarta) was ma-

chined to provide 22 concentric grooves correctly spaced to represent the path of equivalent channels as they appeared on the FM sonar indicator, Figure 6. The outside diameter of the twentieth groove was 5 in. to permit the use of standard 6-in. recording paper. In the bottom of each groove, provision was made for an electrical connection to be carried through the insulating plate.

The grooves were then metalized with copper (metal spray) until flush with the top surface

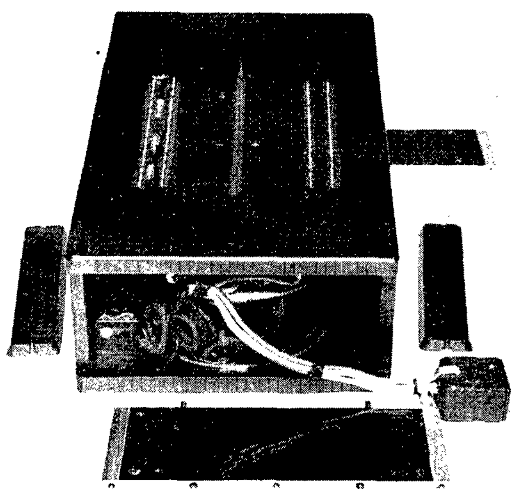


FIGURE 5. UCDWR light valve Model 2 (valve in case with tuning plates and end removed).

of the plastic. This upper surface was then carefully ground smooth. The result of the above process was a plane plate containing 22 concentric copper rings about 90 mils in width, insulated from one another and each separately terminated below the plate.

A small motor was geared to drive the recording paper across the face of the plate at the equivalent of a 6-knot ship's speed. The paper was fed from a magazine provided with an adjustment tension to keep the paper taut. An adjustable air and light gate to exclude light from the magazine and prevent dehydration of the paper was also integral. Above the plate and concentric with the rings was a hinged gear-mounting which supported a Lucite disk. This hinging was to allow loading of the paper. When located in position the Lucite disk was just clear of the paper and the gear engaged a synchro motor. The synchro motor was electrically connected to its corresponding generator at the soundhead column.

Attached radially to the Lucite disk was a small arm with an exterior slip-ring connection. This arm supported 22 recording styli. Twenty of these were, of course, used to simulate the 20-channel form of indication existing at the QLA PPI. The remaining two concentric rings and styli were provided to allow identification marks to be placed on the recording paper, usually by means of a telegraph key. The styli were 0.035-in. stainless steel pins mounted 0.090 in. apart and positioned radially with respect to the concentric rings in the circular plate. The styli were originally hemispherical at the point of contact but were modified after initial tests to provide a broader recording trace. The styli were provided with individual pressure adjustments and were supported in two-way beryllium copper springs. Uniform pressure adjustment was made while the recorder was in operation. The particular design of the PPI recorder was controlled for the most part by the necessity of providing maximum visibility of the recording area. Physical appearance of the unit can be seen in Figures 6, 7, and 8.

7.3.3 Electronic Driver

The sensitivity of the recording paper was such that when placed between electrodes differing in potential by one or more volts a permanent mark was made on the paper. Hence, it was necessary that a driver unit be constructed to transfer the FM sonar detector output signal to the PPI recorder. The initial attempt in this regard was to provide individual cathode-follower circuits which coupled the signal developed at each detector to its corresponding ring on the PPI recorder. A diagram showing this form of circuit connection of an individual channel is shown in Figure 9.

The signal output from 20 such cathode-follower drivers was connected to the 20 con-

centric rings. A threshold control common to all 20 channels was furnished to provide proper recording threshold sensitivity. In operation if the styli and concentric rings were adjusted so that there was zero potential between them, change in potential arising from background noise would cover the recording paper with traces likely to obscure the target indications. To overcome this difficulty the threshold provided negative potential on the styli just above the average level of negative potential developed by background noise. This resulted in a condition where all electrodes printed continuously on the underside of the paper with "no signal." When a target of sufficient echo amplitude was scanned, however, a trace appeared on the topside of the paper.

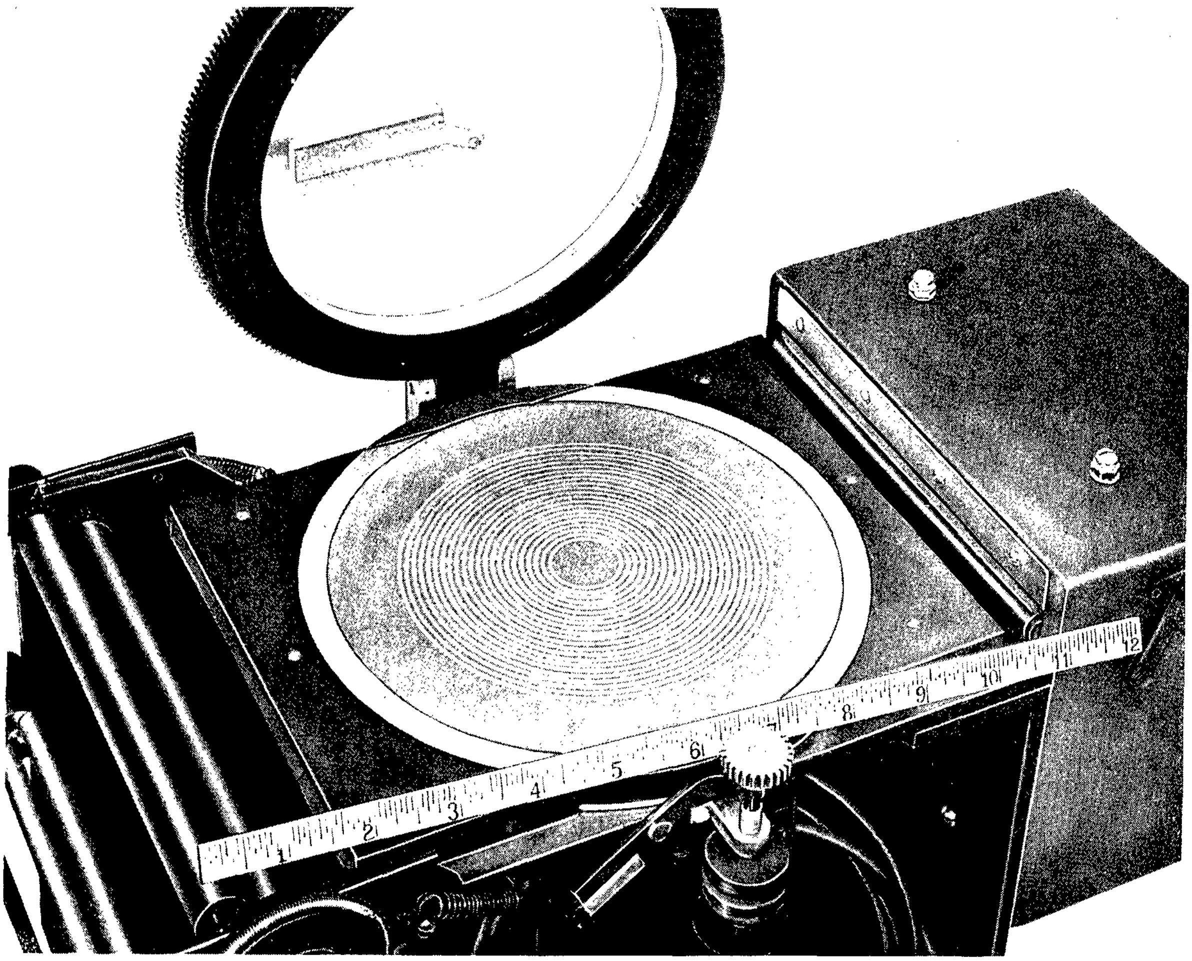


FIGURE 6. PPI (chemical) recorder (oblique view of 22-groove platen).

7.3.4 Tests and Results

The unit was given only one preliminary test. Although the results of this test were encouraging as far as the recorder abilities were concerned, the extreme pressure of other parts of the FM program caused the PPI recorder to be temporarily shelved.

A photostatic copy of the recorder trace obtained in the previously mentioned test can be seen in Figure 10. In the course of the recorder

run shown in the figure, the ship traveled approximately 1,800 yd at a speed of 6 knots.

7.4 DELAY CIRCUIT

In July 1944 there was initiated the development of an artificial water path or delay circuit to be used in bench checking the performance of the FM system as a whole under controlled conditions. The procedure of checking the system in the water had proved difficult and to some extent inadequate because variations in the signal arising from vagaries of the water path exceeded in magnitude the variations in the signal (imparted by the system itself) which it was desired to check.

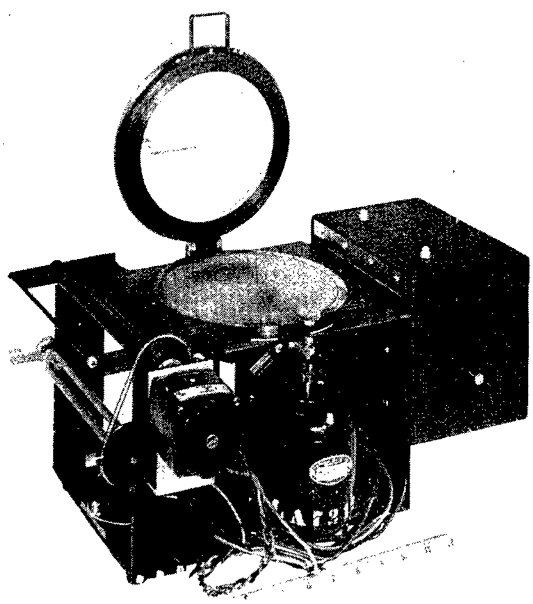


FIGURE 7. PPI (chemical) recorder (oblique view showing driving motor assembly).

Development of the delay circuit proceeded as follows: Two cone-shaped exponential horns made of methyl methacrylate were mounted horizontally on a board and the tips of each cone connected by 8 ft of 0.017-in. diameter stainless-steel spring (Figures 11 and 12). Y-cut Rochelle salt crystal motors attached to the cone bases gave a simulated water-path delay of 0.1 sec (equivalent to about 160 yd). In an effort to increase the delay to 0.5 sec (about 800 yd) five sections of spring supported by nylon threads were joined. Attenuation was too high to obtain response.

Bimorph crystals arranged to give a "bender" effect caused considerable dispersion. A number of suspensions at a point in the spring line, however, filtered out the distortions leaving the transmitted frequency but gave no increase in the 0.1-sec delay time. Switching to ammonium dihydrogen phosphate [ADP] crystals and steel cones (nonexponential) to obtain greater power still gave 0.1-sec delay per 8 ft of spring.

For greater compactness the spring was next wound helically in a squirrel-cage suspension without increased attenuation. The next stage of development, adding booster amplifiers between spring sections and decreasing wire size to achieve greater delay, was interrupted in May 1945 by higher priority projects.

To test a system with the delay circuit the output of the frequency-modulated oscillator [FMO] was fed through a suitable driver amplifier to the crystal motor at the base of one horn, and the crystal motor at the base of the other horn was coupled to the hydrophone connection of the system. The function of the delay circuit produced a difference frequency when the signal received at the hydrophone connection was heterodyned with a sample of the FMO output. The constancy of the difference fre-

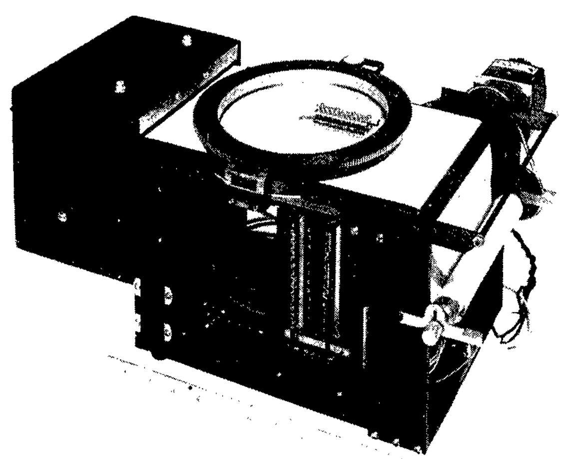


FIGURE 8. PPI (chemical) recorder (oblique view showing recording styli and terminal strips).

quency when monitored by the system itself gave a check on the performance of the system.

7.5 FM SONAR SIMULATOR AND OPERATOR TRAINER[23] EXPERIMENTAL MODEL 1, NO. 1

7.5.1 Introduction

As the name implies, this device simulated both in visual and audible indications the actual operation of FM sonar. Recordings were made during conventional FM sonar scanning to store the audible echo spectrum from different types of targets. Added to these was a 4-kc pulse to index the azimuth from which the spectrum was received.

The simulator was, therefore, an FM sonar analyzer-indicator section using the recordings to replace the units which evolved the difference frequency spectrum. The gear was completed by the addition of equipment necessary to play the spectrum recording and to scan the indicator through an azimuth indexed by the 4-kc pulses. The picture was thus traced on the screen of the simulator just as it appeared on the CRO at the time the recording was made.

In preliminary recordings the sector scanned lay on the bow roughly between about 315 and 45 degrees, relative. In order that the pattern might be oriented with respect to the simulator "bow," a differential drive was incorporated in the sine potentiometer mechanism furnished with the equipment.

7.5.2 Component Parts and Their Functions

It should be emphasized that the experimental model FM sonar simulator and operator trainer was a laboratory production and not designed for service installation. No attempt was made to meet Navy specifications in quality of parts or nature of wiring. The circuits and photographs of the various components are to be found in Figures 13, 14, and 15. The device consisted of the following component parts:

1. A playback unit, a turntable ($33\frac{1}{3}$ rpm), and good pickup. The pickup and phonograph recordings provided an audible signal as originally evolved by FM sonar.
2. A simulator amplifier containing a selective circuit and power supply. This unit amplified the signal from the recording and provided a switching pulse when the 4-kc note was received.

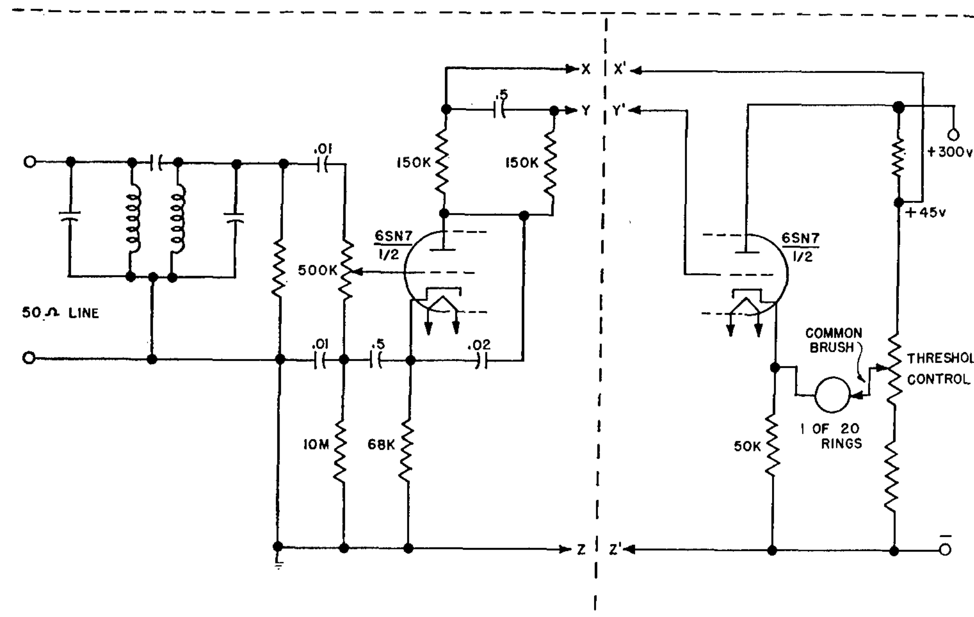


FIGURE 9. PPI (chemical) recorder (coupling stage for one filter channel to recorder).

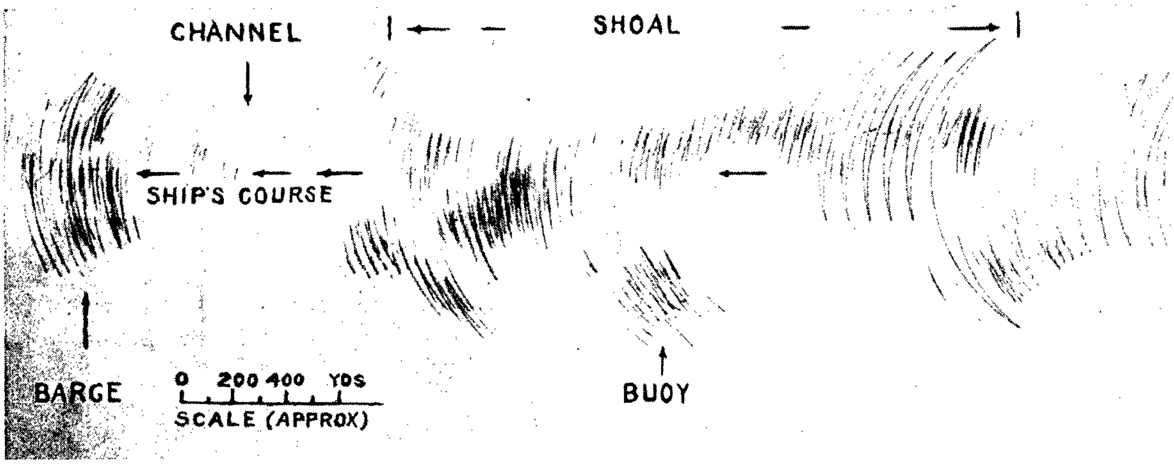


FIGURE 10. PPI (chemical) recorder (photostat of typical recorder trace).

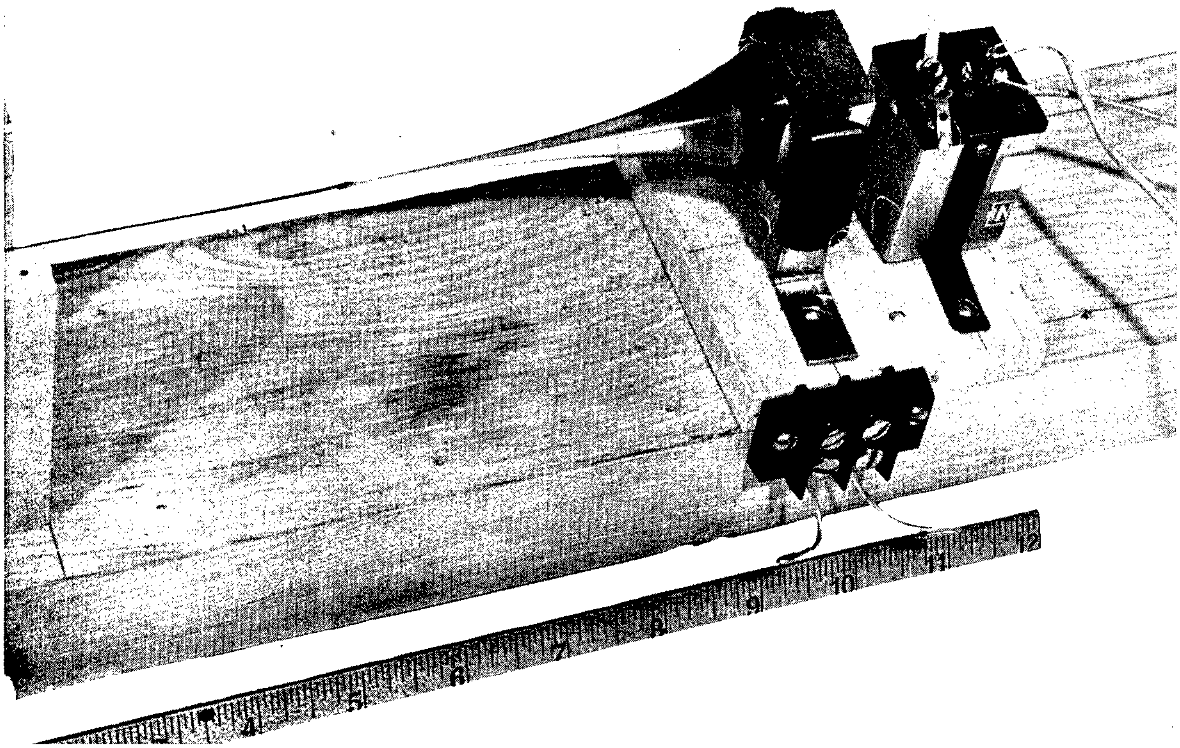


FIGURE 11. Delay circuit (methacrylate exponential horn).

3. A loudspeaker to reproduce the FM signal audibly.

4. A rack containing four chassis. From top to bottom these four were: (a) the motor drive for the sine pot, incorporating differential drive and a reversing relay; (b) a power supply for the indicator; (c) the analyzer chassis containing 20 band-pass filters; and (d) the 20-channel electronic switch. It should be noted that in the Model 1 simulator the switches and the filters were on separate chassis. In the present models of QLA and trainers, the switches and 10 filters

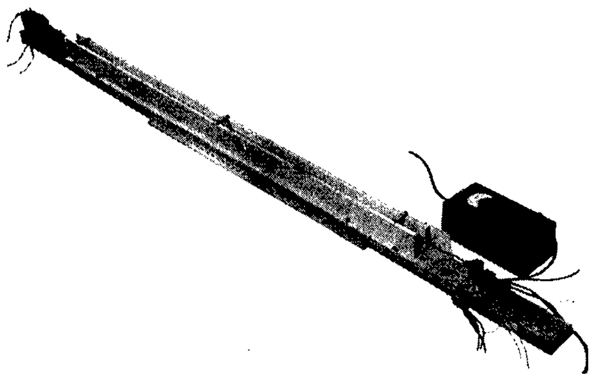


FIGURE 12. Delay circuit (oblique of whole assembly).

are on each of two separate chassis called analyzer No. 1 and No. 2. Aside from this detail and other minor circuit changes, the switch, filter, and the indicator chassis were essentially unchanged from the QLA as currently installed. Their functions were identical and they are described in the QLA manual.

5. The indicator with three extension cables was from an early model FM sonar (Mediterranean). The controls which adjusted and focused the trace, the threshold control, the remote push button, and power switch, functioned as in the regular FM sonar or QLA system. However, gain controls for both input from the phonograph pickup and output to the analyzer were located on the front of the simulator chassis.

6. A motor drive, relay, and sine pot with a differential mechanism for orienting the trace on the indicator.

7.5.3 Simulator Evaluation

Although this unit gave much needed training in aural and visual recognition of QLA

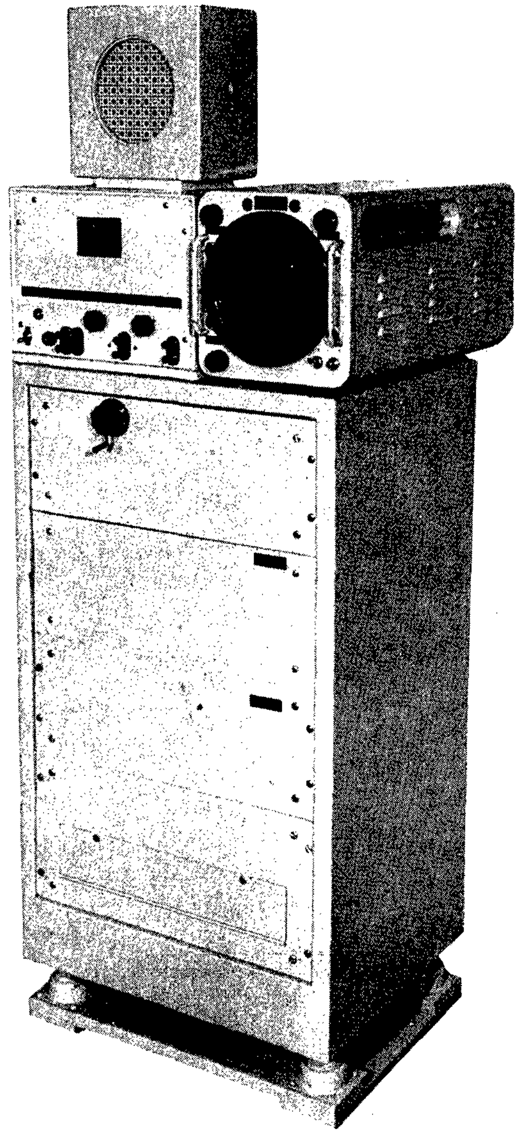


FIGURE 13. FM sonar simulator and operator trainer.

signals it was soon realized that other forms of training were needed. These included control of the gain setting and selection of the range switch as well as control of the sector scan of investigation. It also seemed desirable

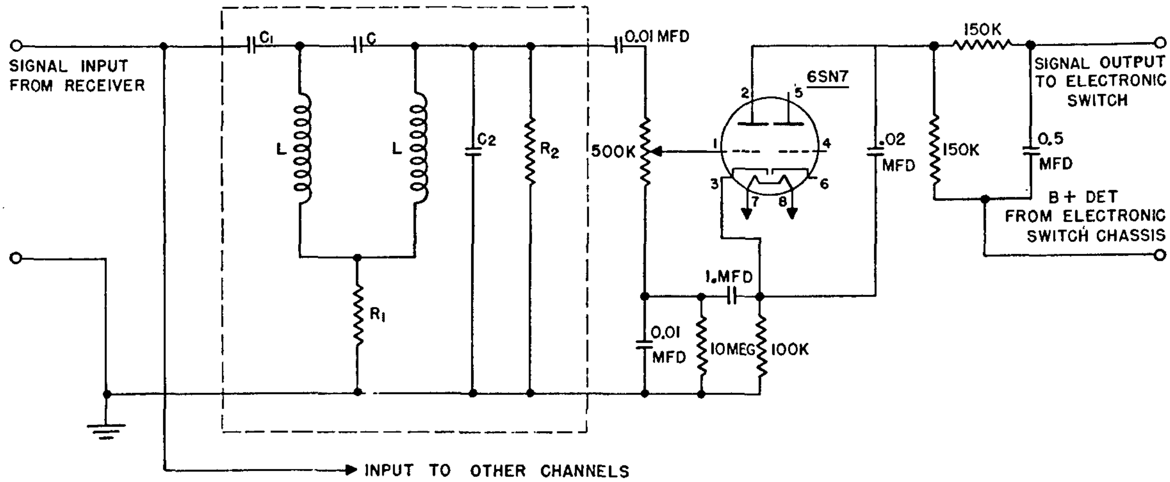


FIGURE 14. FM sonar Model 1 (multichannel band-pass filter schematic).

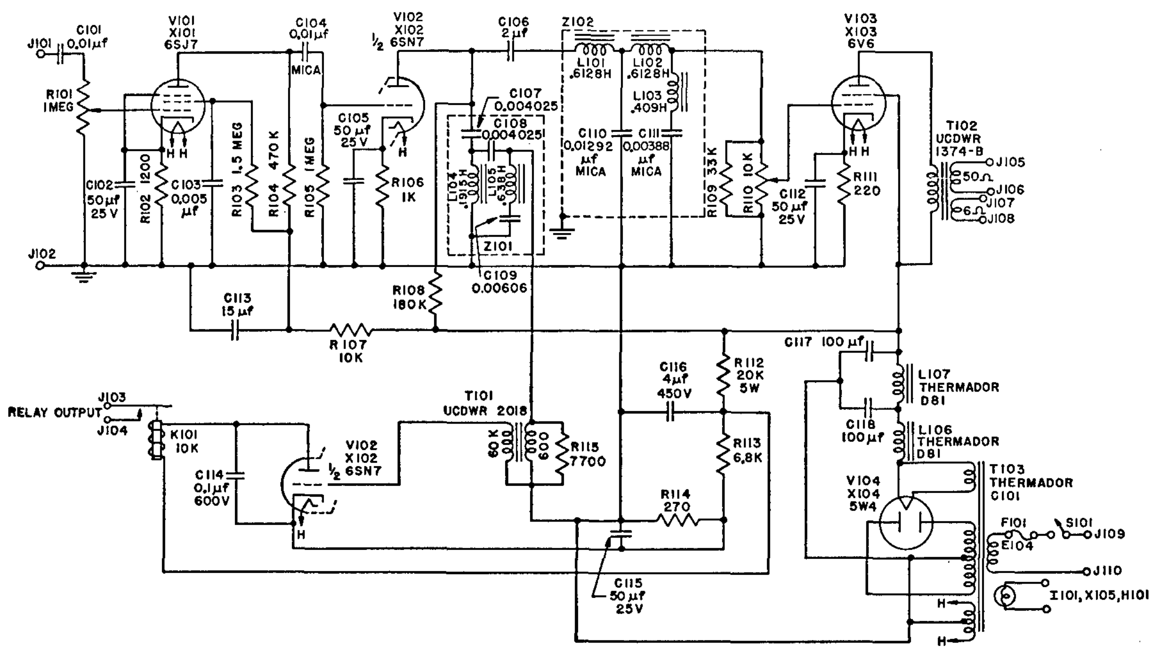


FIGURE 15. FM sonar simulator and operator trainer (schematic).

to be able to set up a problematical situation which would conceivably require maneuvering of the hypothetical ship itself to avoid collision with indicated targets. Such a trainer would allow training of a complete QLA tactical team; i.e., operator, evaluating officer, plotting officer, and conning officer.

Such a QLA trainer was considered at the end of the war with Japan. The redesigned unit can be seen in Figure 13. It is known as the QLA trainer and is discussed in detail in a report of that title.[23]

7.6 CONTROLLED TARGETS

7.6.1 Triplanes

As was mentioned in the discussion of Cobar Mark III, one of the early needs to allow proper

evaluation of the equipment being constructed was the development of a good standard controllable target. The first such target developed

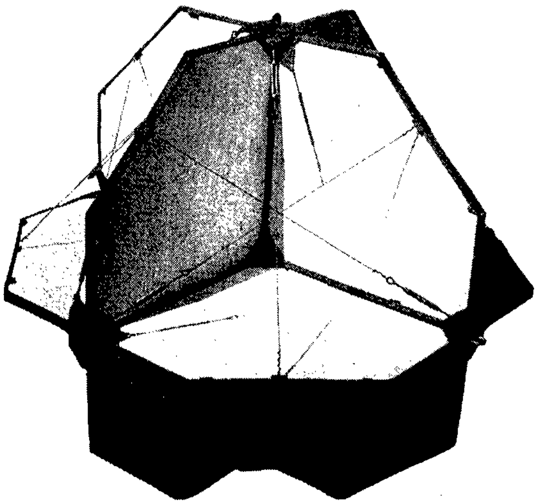


FIGURE 16. Controlled targets (6-ft triplane).

and used to any extent was the 6-ft triplane (Figure 16). It provided a reasonably convenient target roughly equal to a submarine

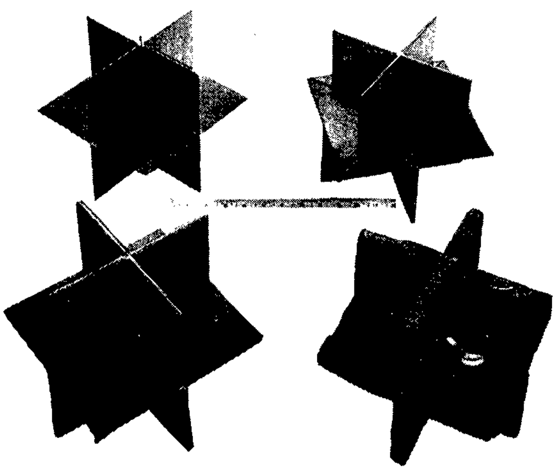


FIGURE 17. Controlled targets (various types of triplane: upper right and lower left covered with Corprene; lower right, foam glass).

in apparent size (or reflection coefficient). For simulation of smaller forms of targets, the triplane was reduced in size according to the extent that an 8-in. unit was used in many of the mine-detection investigations. Although regular 36-in. mine cases were used in the majority of the fundamental measurements with the mine-detecting equipment, the triplanes were

FIGURE 18. Controlled targets (polyplane, or "polyp").

used for much of the equipment checking and student training. Several forms of small triplanes can be seen in Figure 17.

The small triplane provided a useful means of testing the ability of the equipment to detect mines under specific water conditions. It was

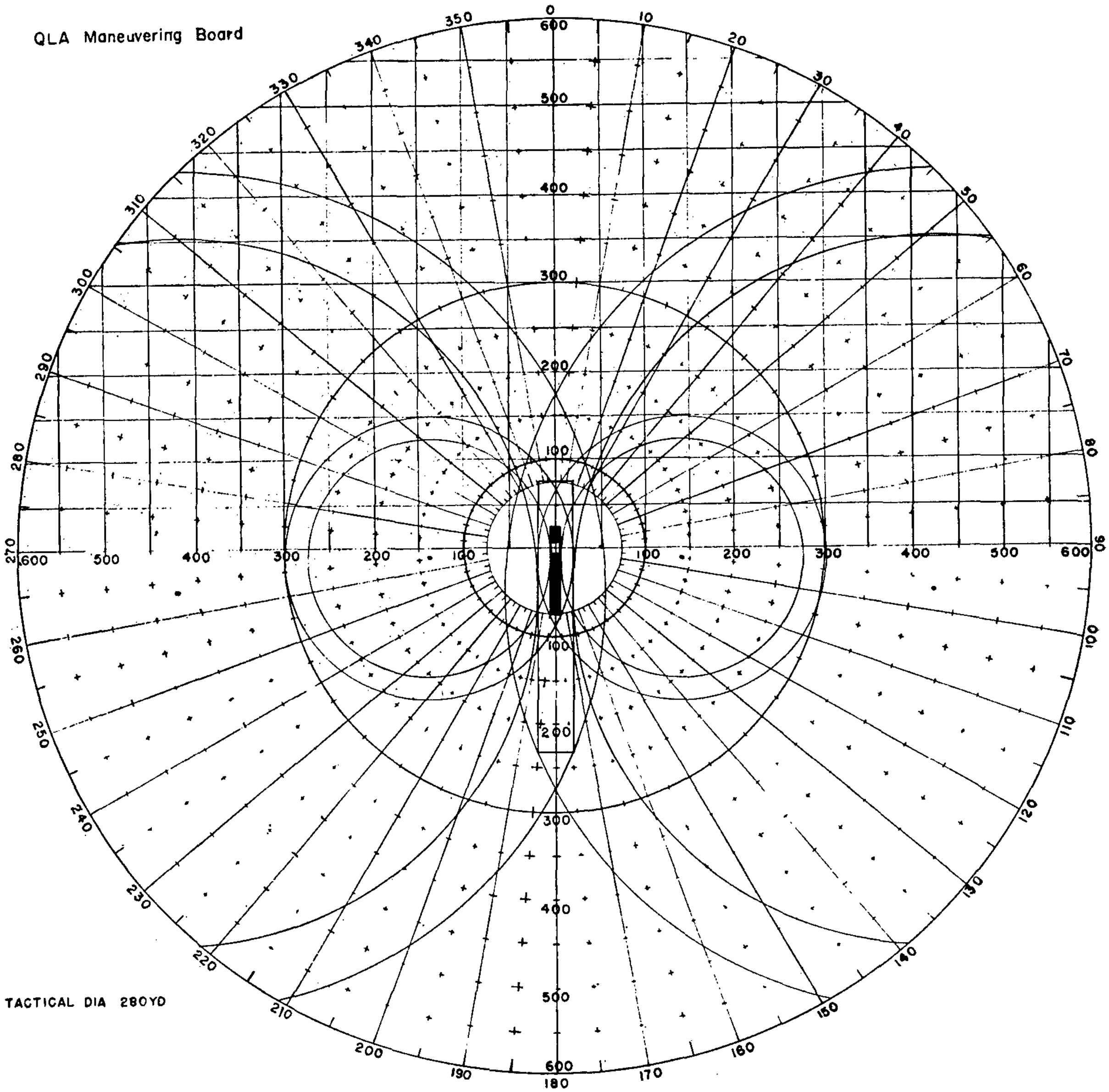


FIGURE 19. QLA maneuvering board.

felt desirable that some such target be available to allow the ships having QLA equipment aboard to spot check both the water conditions and the operation of the equipment. It also seemed desirable that such a target would be considered expendable and automatically sink to the ocean bottom at the end of a prescribed test period. In order to accommodate these requirements the polyplane (Figure 18) unit which was similar in construction and of equal target strength to an 8-in. triplane or 3-ft mine case, was developed.

7.6.2 The Polyplane

The polyplane was an acoustic target of cylindrical outline deriving its name from its struc-

ture. It was composed of two long rectangular planes intersecting at right angles along their longitudinal axis and, in turn, intersected at 3-in. intervals by circular planes at right angles to the common axis of the two rectangular planes. For general usage the term polyplane has been shortened to polyp.

The polyp was developed for checking the overall operation of QLA sonar gear and in determining the gear's effectiveness in small-object detection. It could be used satisfactorily with any gear operating in a frequency range comparable to the 36- to 48-kc band of QLA sonar.

The polyp filled the need for a means of checking submarine QLA sonar without surfacing. Further, the polyp in operation did not itself surface and so escaped detection by enemy surface vessels and aircraft. The polyp could be used to determine water condition limitations on QLA sonar range under tactical conditions.

The polyp was equipped with a buoyancy control so that it could be ejected by the submarine at depths down to 100 ft, and would then seek a level of about 50 ft below the surface in salt water. Target strength was roughly equivalent to that of a 3-ft mine. The size of the polyp ($33\frac{1}{4}$ in. in length by $2\frac{7}{8}$ in. in diameter) permitted stowage of a large number aboard a submarine for frequent use. The device was ejected from the signal gun in the standard manner and had only one moving part.

7.7 QLA MANEUVERING BOARD

This device (Figure 19) is designed to enable the conning officer to determine what action is necessary when a contact is made by the QLA gear. Two scales appear, 600 yd and 600 ft, respectively. The area occupied by the submarine is represented by the two rectangles at the center. A small, filled-in rectangle is based on the yard scale while a larger, open rectangle is on the foot scale. Red parallel lines mark the boundaries of a 75-ft clearance area measured from the outermost extremities of the submarine. The center of the drawing is taken as the center of the soundhead. The fact that the soundhead is about 2 ft off the fore and aft centerline was neglected. The chart thus may be used for either port or starboard soundhead installations. Two circles extending right and left bound the areas which are occupied by the submarine when turning, using a standard twist-ship maneuver (minimum turning-circle diameter). The value used was that obtained by two QLA-equipped submarines. The turning point of the submarine was taken to be 120 ft aft of the bow. It is suggested that each submarine determine its own turning characteristics during the local operations period using either a radar buoy or a simulated target as the contact. The turning circle thus found can be drawn on the QLA maneuvering board carried by the vessel. When using this device the effect of existing currents must be taken into consideration.

Chapter 8

DISCUSSION

8.1 PRESENT STATUS

The previous chapters of this report have dealt with the UCDWR FM systems development program which culminated in QLA-1 during the war. QLA-1 is obviously not the ultimate nor final embodiment of frequency modulation principles. Active development work on this gear was purposely interrupted about two years before this report was written to make possible the construction of models sufficiently well-engineered to be of use to the Navy during the war. Thus, QLA-1 is essentially a late 1943 model. Moreover, it is a specialized piece of equipment, a prosubmarine device for the detection of mines. Axiomatically, specialization is a limiting process, and there are a number of valuable features peculiar to FM operation, which are not available in QLA-1 but which would increase the versatility of the gear were they included.

An understanding of the specialized nature of QLA-1 makes it readily apparent that the broad possibilities of frequency-modulated sonar have so far hardly been exploited at all. It is obvious that further development in the use of a continuous frequency-modulated signal will result in new systems possessing greater versatility, accuracy, and general usefulness.

Any device employing radically new basic principles of operation may be expected to disclose new fields of usefulness. Concentration of attention on the mine-detection problem has resulted in insufficient development of data from which to derive a comprehensive understanding of what all these new fields might be. However, at least two new areas of useful application have already been defined:

1. In connection with problems of plotting it seems clear that the continuous flow of information peculiar to FM operation manifests some real advantages over the conventional pinging method of echo ranging.

2. The alteration of the returning echo frequency by the doppler effect suggests that FM operation may prove capable of providing *instantaneous* measurement of range rate.

The following pages deal with the various tactical applications of sonar gear, discussing in the light of present knowledge the advantages and disadvantages of frequency-modulated systems, and conclude with an attempt to foresee the trends of future development. Discussion of future trends is based mainly upon those ideas which have come to mind in the last two years when demands for the engineering and construction of operable systems forced the suspension of research and development activities.

The effectiveness of projected development programs depends upon several things. Of greatest importance is the requirement that the program enjoy the services of competent physicists and electronic engineers who have wide experience with sonar devices and their operation at sea. In addition it is equally important that these men be continuously and adequately informed of changing tactical requirements for sonar gear.

8.1.1 Tactical Applications

The basic job of a sonar system is the detection of submerged objects which are undetectable by any other method. In addition to mere detection the system should measure range, bearing, range rate, target aspect, depth, etc. In the operation called plotting these measurements are so arranged and related that some of their future values may be predicted. Tactical usefulness of the system is primarily dependent on these predicted values rather than the existing values. This point of view is fundamental to the tactical evaluation of any sonar system.

When the FM program was undertaken by UCDWR, the main tactical application of the system was expected to be in the work of submarine detection. However, as previously pointed out, emphasis shifted during the course of the recent conflict to application of sonar systems to submarine use for the detection of

mines. It would be unfortunate if FM techniques were to be considered useful only for small-object detection (because QLA proved reasonably successful in this application) and their broader applications overlooked. The prejudice which holds FM sonar as essentially a submarine-mounted device is easily traceable to the system's recent history and may not be detrimental to its future since it appears that submarines may have a larger part in future naval operations than they have in the past. It is equally true that peacetime applications of sonar methods may increase and that these applications will be made by surface vessels.

Passing over sonar measurement of ocean depths, sonar detection finds its most important target to be the submarine. In most cases the submarine is detected for the purpose of attacking and destroying it. Such a purpose involves launching some weapon in such a way that it and the submarine are at the same point in space at some subsequent instant of time. The effectiveness of this undertaking depends directly on the accuracy with which the submarine's future position may be predicted from sonar information.

During World War II visual or radar information was often used to initiate an attack on a surfaced submarine, and sonar detection was only used in the latter stages of the attack after the submarine had submerged. With the ever-increasing submerged endurance of underwater craft it seems probable that attempts to destroy them will soon have to be guided entirely by sonar information. The task will be complicated by the high underwater speed and ability to dive deeply which will assuredly be characteristic of submarines of the future.

These considerations indicate that future sonar gear must provide more diversified and more accurate information to the plotting table at a more rapid rate than has been possible in the past. For successful prosecution of an attack on a submarine of the type suggested above, a spotty knowledge of range and bearing will not be sufficient. Additional information on depth, target aspect, range rate, etc., will be needed and since the submarine is guided by a human intelligence bent on escaping destruction it is essential that all this information be made available rapidly and continuously to the plotting room. It remains for the future to determine to what degree frequency-modulated sonar can fill these requirements.

Except for the evaluating of new devices and the scoring of maneuvers it is not essential that a plot retain much history. It is more important that data on present events reach the plotting table after a minimum time interval. Automatic plotting is more efficient in this respect than are procedures requiring the intervention of human agencies. In the present state of the art, automatic plotting seems best accomplished by a PPI portrayal on the face of a cathode-ray oscilloscope. In this connection it seems probable that application of the radar skiatron to sonar portrayal problems would have value. Since here the image is projected on a screen, pencil plotting methods may continue to be employed. It is strongly recommended that skiatron presentation methods be adapted for use with frequency-modulated sonar.

The foregoing discussion of submarine detection is equally applicable to navigational problems of which mine detection is the most important. Combat experience has shown the very great importance of plotting in making a transit of a mine field. Mines and other navigational hazards rarely occur singly (mine field transits frequently require that a course be taken in relation to four or more mines at a time) and the wide-angle coverage of a PPI system is almost a minimum requirement under these conditions.

In the past, torpedo detection has been dependent upon listening techniques. Recent and projected advances in the torpedo art render listening detection of these weapons a doubtful probability. Here again a 360-degree PPI presentation of echo-ranging information may make it possible for a ship to avoid a torpedo successfully. QLA-1 equipment has demonstrated its ability to detect torpedoes both by listening and by echo ranging at considerable ranges but these ranges may prove inadequate to future tactical requirements. It now seems probable that some modification in QLA sonar will extend the range of detection of such small objects. (This modification is discussed later in Section 8.2.6.)

A sonar task similar to detection of torpedoes is the protection of anchored vessels from sneak weapons of various sorts. This acoustic problem is complicated by the fact that such weapons are usually very small and are generally encountered in shallow water (harbors and roadsteads) where echo ranging is difficult. It is a problem for which a sonar answer should be sought.

The success which has already been achieved in the development of nonreflecting coatings indicates that target strengths of various objects, from submarines to mines, may be expected to decrease progressively as the nonreflecting coatings are improved. This trend increases the demands on sonar equipment particularly in the field of small-object detection. As target strengths become smaller and smaller, a premium will be placed on the ability of sonar gear to disclose the nature of the reflecting object so that a true target may be differentiated from false target indications arising from fluctuation, reverberation, fish or other organic life, etc. Ultimately target definition may present a picture of the object on the PPI screen and true targets will be identified by the shape of the indication rather than by size, repetition, character of the tone from the loudspeaker, etc.

In the light of the foregoing rather general remarks the following discussion deals with the advantages and disadvantages of the present FM system (QLA-1).

8.1.2 Advantages of the Present FM System (QLA-1)

Feasibility of Manufacture

Scanning sonars are inevitably complicated electronic devices. It is conceivable that a system could be so complicated and so difficult to adjust that its manufacture by standard industrial methods would be impracticable. To have real value to the forces afloat a scanning sonar must lend itself in some degree to industrial assembly-line production techniques. The fact that over 50 QLA systems were built by standard manufacturing methods during World War II demonstrates that this particular device is manufacturable.

Plan Position Indication

The *plan position indication* [PPI] employed by QLA sonar has many advantages of naturalness and interpretability. This was well demonstrated by the ease with which sonar teams became skilled in the use of this gear. This is an advantage not peculiar to the frequency modulation method but common to all scanning sonar systems. The very naturalness of this type of indication lends itself particularly to plotting.

Continuous Transmission

In the light of present knowledge it appears probable that the frequency sweep method described in this report represents the only practical method of utilizing a continuously radiated signal producing a continuous echo. The use of a continuous signal producing a continuous echo affords three very real advantages: (1) information is made available to the plotting or conning officer at a very rapid rate; (2) in normal searching operations the time required for one complete revolution of the soundhead is the only limiting factor on rate of coverage (with extreme rates of revolution filter characteristics may become the limiting factor); and (3) for sector scanning (within the 80- to 90-degree angle illuminated by present transducers) the angular motion may be as rapid as mechanically practicable.

Ability to Scan Rapidly

The present FM system (QLA-1) is designed to scan 360 degrees at a rate of about 6 rpm, which is adequate to most of the tactical purposes for which QLA sonar has been used. The 6-rpm limit is set by the width of the transmitted beam versus target range and corresponds to an angular speed so that the sound from the leading edge of the transmitted beam may reach a target and return by the time the center of the receiving beam comes to the same azimuth. Thus 6 rpm corresponding to 36 degrees (approximately the half-width of the transmitted beam) per second is adequate for searching to about 800 yd. For searching to greater ranges a slower speed is used.

If the transmitted beam were to be made nondirectional, a scanning rate of at least 120 rpm would be available; but at this rate the build-up time of the filters would probably soon become a limiting factor (150 rpm theoretical limit).

Echoes Received Audibly as Well as Visually

In the operation of sonar gear the great acuity of the ear is a very desirable adjunct to the eye in the initial detection of an echo, and the ear is still the most important means of determining the character of a target. Bursts of reverberation, shoal and kelp echoes, etc., have a very different tonal quality from mine and submarine echoes. Aural presentations of the former are mushy and fuzzy, whereas the latter give rise to clear bell-like tones whose frequency depends upon the range of the target. The characteristics of QLA sonar are such that objects whose range is too great or too small to give beat frequencies which may pass through the filter can be heard by the ear before they have reached ranges which allow them to appear on the screen of the CRO.

Pulse Duration Discrimination

As explained in early chapters of this report, the CRO screen of QLA sonar is kept relatively free from extraneous indications because the system is designed to accept pulses whose duration lies between two fixed limits. This pulse duration discrimination is accomplished with two *RC* networks: one in the grid return of the detector tube which follows each one of the analyzer filters has a time constant of about 5.0 sec; and the other, forming the plate load of each of the same tubes, has a time constant of about 0.1 sec. The combined effect of these two networks is to discriminate against pulses with duration of less than 0.1 sec (noise) and against pulses with duration of more than 0.5 sec (reverberation). Under this arrangement the system's visual indication is relatively more responsive to pulses of moderate duration

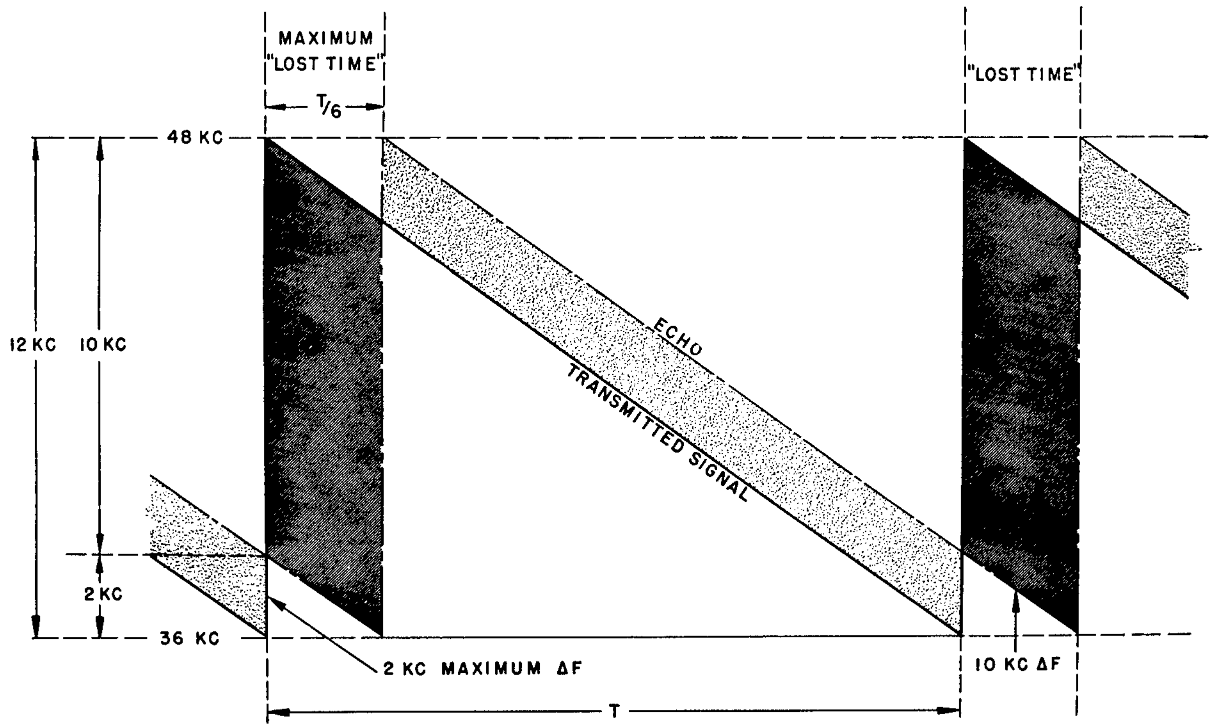


Figure 1. Lost time associated with recycling of the sawtooth.

(between 0.1 sec and 0.5 sec) arising from the action of the hydrophone beam scanning across the target than it is to reverberation and noise.

Ability to Detect Small Objects

As described earlier in this report, QLA sonar has marked abilities in small-object detection which although not yet entirely satisfactory have been adequate for certain strategic operations.

Security

A measure of security against detection by the enemy was obtained for users of QLA during World War II. This arose solely from the fact that QLA operated at a higher frequency than was customarily used by other navies. It would be idle to pretend that this so-called advantage has any future significance for it may be assumed that any future enemy will equip himself with apparatus to explore the entire frequency spectrum. Under these conditions any frequency may be detected.

8.1.3 Disadvantages of the Present System

Lost Time

To delineate briefly the problem of lost time, reference is made to Figure 1 in which it is apparent that (in the case of an echo returning from a target so far away that over the majority of the sawtooth excursion the difference between echo and transmitted frequency corresponds to the maximum of 2,000 c) there exists a maximum lost time of one-sixth of a cycle during which the difference frequency is 10 kc. The 10-kc frequency is too high to pass through any of the filters, and consequently during this portion of the sawtooth excursion there is a blank on the cathode-ray screen. This was particularly troublesome in mine-detection operation since an operator would occasionally lose a target in the lost-time gap and several precious seconds might go by before he found it again. One method of avoiding this difficulty is to arrange the limits of scan so that the lost-time gap occurs at about bearings 300 degrees and 060 degrees relative when searching dead ahead.

In the interval between the end of the war with Japan and the present writing, another solution to the problem of eliminating the lost time has been found by UCDWR. From Figure 1 it is obvious that an echo which would normally occupy the outer channel (at 2,000 c) has the maximum lost time during which difference frequency is 10 kc. If this 10-kc signal is picked up at the output of the first detector and heterodyned with a 12-kc local oscillator there results a difference frequency of 2 kc, so that the echo now gives a 2-kc difference frequency over the whole frequency modulation cycle. Further, an echo which would normally fall on the innermost channel (difference frequency of 500 c) exhibits a difference frequency of 11½ kc during its much shorter lost-time period. This difference frequency when heterodyned with the output of the 12-kc oscillator produces a 500-c note so that here again a constant frequency is observed throughout the frequency modulation cycle. This discussion has been somewhat oversimplified in that it neglects the effect of the doppler shift in frequency (see following text). For the present purpose it need only be noted that since the doppler shift is greater at the higher frequency the echo from a moving target gives rise to an echo frequency sawtooth which has a different slope than the undopplered sawtooth. It can be shown that over the lost-time period and for all ordinary range rates this shift is insignificant and the above suggested method is applicable.

Range Error Due to Doppler

As discussed in Chapter 2, the modification in frequency due to the doppler effect falsifies the range as presented on the PPI oscilloscope screen. The specific application for which QLA sonar was engineered during World War II was such that this range error was unimportant because in the case of a submarine making a submerged transit through a mine field the velocity of the submarine relative to the mine was always small. In future applications of frequency modulation techniques, however, it may not be possible to neglect the doppler error. Since the error arises from range rate, means should be sought not only to correct for the error but to utilize it as a measurement of range rate.

One method of accomplishing this indirectly has already been described in Section 4.3. Here the doppler effect was utilized to give velocity compensation for ahead-thrown weapons. In this application the weapon was fired at the instant the Subsight equipment indicated that the submarine (target) was at the correct range. Because of the doppler effect this Subsight indication was given at a range that allowed for the time of flight (and sinking time) of the weapon. This method should be applicable to a number of similar problems in the future.

A second approach to this problem has been under development since the end of hostilities with Japan. Figure 2 is a block diagram of a modified FM system that permits both (1) a more accurate measurement of the range of a particular target once it has been located with the FM search on the PPI, and (2) a measurement of the doppler effect itself and hence of the relative range rate. This system utilizes a second CRO similar to a radar A-scan in which the horizontal axis measures time or range and the vertical axis receives signals to produce two pips (one marking true range and one marking apparent range) at least once in each FM sawtooth period. A long-persistence screen permits measurement of these pips. To measure the range a "step" in the horizontal sweep may be brought into coincidence with the first pip by means of a range knob, and the range can then be read on a Veeder counter. The second pip which is separated from the first by a distance proportional to the doppler error may now be brought into coincidence with the first pip by means of a range-rate knob and relative range rate may be read on another counter.

For this modified FM system the outgoing signal is generated and radiated into the water in the conventional manner. The modification consists of a unit added to the present receiver to supply the range and range-rate information on a second CRO. The horizontal sweep of this CRO is controlled by a sawtooth voltage generator operating at six times the sawtooth frequency of the frequency-modulation oscillator [FMO]. The initiation of each sixth horizontal A-scan CRO sweep is synchronized with the flyback of the FMO sawtooth signal.

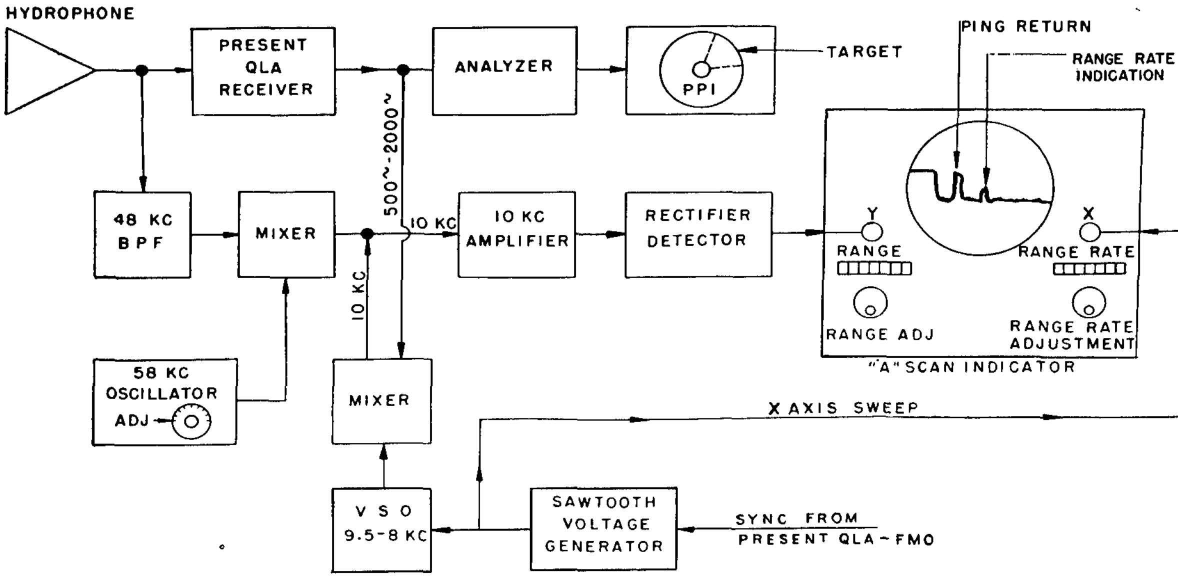


FIGURE 2. Instantaneous range rate determination, functional block diagram.

The first pip, labeled *ping return* in Figure 2, indicates true range, and is obtained by utilizing the initial portion of the FM signal as a ping. The position of the pip depends upon the time interval elapsing between the flyback of the FMO transmitting a signal at 48 kc and

the first return of this signal as an echo. The fact that there may be a doppler shift in frequency does not interfere with the measurement of this time interval. The echo received by the hydrophone is passed through a band-pass filter. This filter is centered at 48 kc and is of adjustable width to accept any doppler shift from 48 kc. Thus, only the first portion of the echo to return during each sawtooth cycle is accepted by the A-scan unit. This signal of frequencies close to 48 kc is amplified and applied to the vertical axis of the CRO giving a pip on the horizontal trace. (It would seem convenient to convert the carrier frequency from 48 kc to 10 kc by mixing with a 58-kc local oscillator. This may simplify the filtering problem.) The time interval between the initiation of the FMO flyback and the initial return of the echo is measured by adjusting a step in the horizontal sweep to coincide with the ping return pip, the range then appearing on a Veeder counter associated with the range knob, a technique like the radar A-scan.

The output of the present QLA receiver consists of frequencies lying between 500 and 2,000 cycles per second. For the modification under discussion it is also proposed to measure these frequencies by using the panoramic technique with a sweeping oscillator and a fixed filter in addition to the regular analyzer of the PPI system. The output of the receiver is mixed with another signal from a local voltage-sensitive oscillator [VSO] whose frequency is varied from 10 kc to 8 kc by the A-scan horizontal sweep generator. This sixfold sweep is synchronized with the FMO sawtooth in such fashion that its frequency reaches 8 kc at times which are $\frac{1}{6}$, $\frac{2}{6}$, $\frac{3}{6}$, etc., along in the main cycle. The heterodyned mixture of the VSO and receiver frequencies is fed to a narrow 10-kc band-pass filter and whenever the sum of these two frequencies is 10 kc, the energy is amplified and applied to the vertical axis of the CRO. The position along the horizontal axis of the resulting pip is thus determined by its frequency which is in turn determined by both range and range rate. Thus the separation between the latter pip and the first or ping return pip is proportional to the doppler error. This separation may be measured by bringing the two pips into coincidence by means of a range rate knob. This knob controls the average frequency of the local VSO, shifting it up or down by a calibrated amount and thereby shifting the dopplered pip back and forth along the horizontal axis. At the time of writing this report this development seems a good starting point for the elimination of range error and the introduction of a range rate meter. It will be noted that this new range and range-rate indicator in no way interferes with the ability of the PPI system to perform rapid search.

Mechanical Rotation of the Transducer

The way in which the QLA transducer is rotated in azimuth was found necessary during the war to adapt the system to existing ships without major modification. It would be much more satisfactory if all the moving parts were within a housing which protected them from the sea water. Thus, for example, a better arrangement would be one in which the transmitting transducer was stationary and radiated through 360 degrees with the receiving transducer rotating at higher speed inside a dome or other housing.

Limited Range

In any discussion of the limited range of any sonar equipment it is well to keep in mind the many factors responsible for such limitation. Among these may be listed energy reaching the target, which may be lessened by thermal refraction or attenuation as well as divergence of the beam; and background which may be due either to reverberation or to noise including both self-noise due to the ship's motion and that due to the electronic circuits within the system.

In the early days of experimental work on frequency modulation systems in San Diego, circumstances were such that much of the testing at sea had to be done during the summer months when thermal conditions were quite adverse to such work. The maximum range of detection was quite short for all sonar gear under these conditions and it was not until further tests were made during winter months in more isothermal water that it was recognized that insufficient energy radiated by the projector was a limiting factor on range. This led to a

redesign of the projector until present QLA systems are now putting out as much energy per unit of solid angle as are any other standard sonars.

It may be reasonably expected then that QLA is no more limited by this factor than any other system, and this is borne out by some of the experiences during the war with mine detection. The usual ranges encountered around San Diego where sound conditions are rather poor lay between 200 and 500 yd. In the better sound water of the Pacific, ranges over 1,000 yd and occasionally over 2,000 yd on mines have been reported.

At slow speeds and with the type of electronic construction employed in QLA it is not expected that noise due to the motion of the ship or to the electronic component will be any higher than that encountered in other sonar equipments. At higher ship's speed, however, more noise due to motion may be expected with all sonar equipment and this suggests that future development must envisage some streamlining of the transducer. In the matter of noise caused by reverberation the designer has some control since the magnitude of reverberation is dependent upon pulse length. As explained earlier an effective pulse length can be assigned to a frequency-modulation system equal to the bandwidth of the filter in the analyzer divided by the rate of change of frequency. The use of narrower analyzer channels would effectively shorten the pulse length and therefore reduce reverberation.

In most respects the frequency modulation method should not be limited in range any more than any other sonar except by underway noise and by reverberation, and means exist for correcting both of these factors. These statements are undoubtedly made on the basis of too little information. Therefore every effort should be made in the future to make more measurements and do more analysis on this problem.

Dependence of Pulse Length on Range Scale

As mentioned previously, a frequency modulation system can be assigned an effective pulse length, which is equal to the bandwidth of the filters divided by the rate of change of frequency. The rate of change of frequency is the maximum frequency excursion divided by the sawtooth interval. In changing from one range scale to another it is this sawtooth interval which is altered. Consequently on long-range scales the effective pulse length is longer than it is on short-range scales. For example, on a 2,000-yd scale the effective pulse length is about 100 msec while on a 100-yd scale it is only about 5 msec. In the case where reverberation is the limiting factor against detection it follows that, in general, QLA sonar performance is somewhat impaired at the higher range scales. The value of reducing the effective pulse length is nowhere more strikingly illustrated than in a modification of QLA sonar which makes the sawtooth period extremely short. Reducing the length of the sawtooth period to a value associated with a maximum range of 50 ft provides an effective pulse length of about $\frac{3}{4}$ ms, and brings all difference frequencies (between transmitted signal and returning echo) within a very narrow band so that a 20-channel system employs extremely narrow filters (in width of range annuli). A unit so modified can detect ultrasmall objects, such as a string of six paper clips or a target smaller than a penny match box out to distances of 25 ft to 30 ft.

Attenuation Due to Higher Operating Frequency

The original decision to operate QLA systems in the region between 36 and 48 kc was quite arbitrary. No departure from this band was made during the war because it would have called for a redesign of all transducers which would have materially slowed up the development work. Cutting the operating frequency 50 per cent to bring it down to the customary sonar band would have involved increasing the size of all transducers by a factor of two and would have also involved the use of larger crystals in those transducers. During the war such changes would not have been expedient, but at this writing an alteration in frequency introduces no such problems. On the other hand there are many conceivable applications of the frequency modulation method which would suggest an upward change in frequency. It would seem best to regard the attenuation at higher

frequencies as no real disadvantage of the method but simply as a design parameter which can be altered to fit requirements.

8.2 A PROGRAM FOR FUTURE DEVELOPMENT

The discussion in the last section suggests that most of the outstanding difficulties with the present QLA version of frequency-modulated sonar may be susceptible to considerable amelioration. With the cessation of hostilities and with a considerable relaxation in the need for assisting the forces afloat in the installation and use of QLA sonar in actual combat, it is appropriate to propose a plan for future work on this device. Such a plan may form a basis for immediate work to be supplemented in the future as new problems and applications arise. Before considering such a plan in detail, emphasis must once again be placed on the fact that the stress of work during the war years was such as to reduce to the necessary minimum all analytical work and experimental evaluation of this device. These matters are not treated in detail as the need for further analysis and evaluation is obvious. The same sort of studies of frequency modulation echo ranging need to be made as have been made for ping echo ranging. The remainder of this chapter is devoted to a discussion of a number of ideas and suggestions which have arisen during the past two years which may well contribute to improved performance of frequency-modulated sonar.

8.2.1 Elimination of Lost Time

As indicated in preceding text one method of accomplishing this has been suggested and partially reduced to practice. This needs considerably more study and evaluation under a variety of conditions at sea.

8.2.2 Improvements in Indicators

One method (other than Subsight) of making use of the doppler shift in frequency to provide instantaneous range rate measurement was mentioned in preceding text. This proposal visualized the addition of a second cathode-ray oscilloscope indicator to the system utilizing a display analogous to the Type A indication of radar. It seems fairly clear that a PPI indication is valuable for certain uses but that additional indicators may be needed to provide other types of information and possibly for more accurate presentation of information.

In this connection, means should be sought whereby a particular area on the PPI plot can be chosen by the operator to be expanded on another CRO. The purpose of this expansion might be to give him a chance of making a more accurate determination of range and bearing. It is also conceivable that this expansion might ultimately be used to determine the nature and aspect of a target if a higher degree of definition can be achieved in the system.

Another possible improvement in indicators which should be tried with FM sonar and evaluated for its tactical value involves the use of dark-trace cathode-ray tubes or skiatrons. With such a tube it is possible to project the PPI trace greatly enlarged on a plotting table. With cathode-ray tubes of quite ordinary dimension the trace may be enlarged to a diameter of at least 30 in. It is conceivable that such enlarged plots would make the information available to the conning officer in a form more accurate and more quickly interpretable.

As mentioned in later text, certain proposed changes in the range and bearing cursor suggest the possibility of coupling a target indication directly to a target positioner on the dead reckoning tracer.

8.2.3 Slip Rings

As indicated earlier in this report, some of the earlier models of FM sonar employed slip rings to connect the hydrophone and projector to the electronic stack with some measure of success. The principal difficulty encountered here in addition to noise was the fact that because a continuous signal is being sent to the projector the degree of isolation between the projector and receiver slip ring must be high. Slip rings were abandoned because of the necessity of producing a serviceable model of FM

sonar for immediate use. On several occasions some difficulty has been experienced in the field with limit switches. Moreover, the limitation that the soundhead should never rotate more than a certain given amount in one direction somewhat reduced the flexibility of the system. Consequently it is highly desirable that a vigorous attempt be made to develop a suitable slip ring arrangement. As this is being written, some work is going on toward modifying the standard TDM slip rings to this purpose. It will probably be necessary to devise an arrangement specifically designed for FM sonar.

8.2.4 True Bearing Scale

This is a perfectly straightforward modification of existing QLA gear which may be made in a number of different ways. It is highly important here that an evaluation of the desirability of such a change be made in cooperation with the forces afloat because the need for bearing indication depends largely on the way in which information is being used. Whether it is desirable to present both true and relative bearing simultaneously is a decision which will influence the choice between the two alternative methods to be described.

In one of these, rotation of the sine potentiometer would be controlled by appropriate connection to the ship's gyro. In this case the presentation on the cathode-ray screen would then be oriented so that 000 degrees true would be at the top of the screen.

The second method involves connecting a true bearing scale (encircling the CRO screen) to the ship's gyro so that it would rotate as the ship's heading changed. This scale would be in addition to the relative bearing scale which would remain fixed with respect to the indicator cabinet.

8.2.5 Electronic Modifications in the Receiver

In the opinion of the electronic engineers who have been associated with the development of frequency-modulated sonar, the present design of receiver is not entirely satisfactory. The problem of matching it to the impedance of the hydrophone is not entirely solved. This development would go hand in hand with any further development of the hydrophone itself, specifically in the direction of improving the flatness of its response. Moreover, at the present time the passive networks which precede the amplifying stages of the receiver introduce more loss than is desirable.

8.2.6 Improved Mine and Torpedo Detection

Increasing the number of channels in the frequency-modulated sonar system (in addition to improving range resolution) would shorten the effective pulse length, and should considerably improve the ability to detect small objects such as mines and torpedoes. With the probable marked decrease in all target strengths in the future, due to the general employment of reflection-reducing coatings, it is of the greatest importance that every possible step be taken to improve greatly the ability of sonar systems to detect weak echoes. To this must be added the very great likelihood of a more widespread application of midget sneak weapons which demand a system alert to the weak echoes returning from such devices.

Not much attention has yet been paid to the development of frequency-modulated systems as passive listening devices. Conceivably, the wide frequency band through which they work can make them more useful than standard single-frequency devices for this purpose. This becomes of importance in connection with the detection of torpedoes. Despite the fact that every effort is being made to make these weapons quieter, every increase in the speed at which naval action takes place, undoubtedly though perhaps only temporarily, brings noisy torpedoes back into use. Some experimenting with the amplifying characteristics of the receiver is suggested, therefore, in order to make FM systems as good listeners as is compatible with their use as an echo-ranging device. Such development should in no way impair the latter ability, for an echo-ranging contact on a torpedo is very much more to be desired since it

gives range as well as bearing to assist in taking proper evasive action. Naturally, if the torpedo is acoustic, it may be necessary to avoid the radiation of sound and detect it solely by listening.

8.2.7 Improvement in Bearing Accuracy

Scanning systems, if they are to be used at all for fire control, need some improvement in the available bearing accuracy by a device which would perform a function similar to that of the *bearing deviation indicator* [BDI] in pinging systems. Possible solutions to this problem have been suggested.

One solution proposed involves a fairly straightforward application of bearing deviation indication methods. The fact that the frequency varies throughout a modulation cycle would cause the lobes of the BDI to move in synchronism with the sawtooth wave. Their crossover point would not be disturbed, however, and possibly this phenomenon can be utilized.

Another suggestion involves the use of a split hydrophone, the two halves of which are connected out of phase (with each other). The pattern of such a hydrophone is characterized by a deep minimum corresponding to low sensitivity for sound incident normally on the hydrophone. This minimum has very steep sides and should give a spot on the PPI screen with a very narrow dark line through it which would correspond to the center bearing of the target. Preliminary experiments have indicated that this is indeed the case.

8.2.8 Improved Range Accuracy

Range accuracy may be improved in a number of ways. One of these has been discussed in some detail earlier in this chapter in connection with the doppler error where it was suggested that by using part of the sawtooth as a ping and employing methods similar to those used in radar a simplified doppler-free measurement of range would result. Another aspect of this problem concerns an increase in range resolution by narrowing the filters and concomitantly increasing the number of channels used to analyze a given spectrum. One means for accomplishing this, which provides not only greater range resolution but also more rapid analysis, has been discussed by Sidney Bertram.[17] He proposes to multiply the frequencies by 100 (for example) before analysis so that the original 500- to 2,000-c range would appear as a 50,000- to 200,000-c range. If this range were resolved into 100 channels, each band would be 1,500 c wide and the transformed band could be analyzed in a much shorter time than the untransformed one. A possible recording system for this arrangement would utilize a medium-persistence CRO as a recorder and an iconoscope as a pickup. Thus the signal could be impressed continuously as a circular trace and then scanned by the iconoscope describing the same circle but 100 times as fast. It is clear that the development of such a device would raise a host of problems, but it does seem that this proposal offers one means of achieving rapid analysis and extreme range resolution.

8.2.9 Improved Range and Bearing Cursors

Whether or not improvement can be made in range and bearing accuracy, there seems to be a real advantage in modifying the present method of reading the indications on the PPI oscilloscope screen. As a means of avoiding parallax and the confusion of a reticle before the screen, it has been proposed that electronic cursors be used.

The bearing cursor might appear on the CRO screen as a radial line of light which could be illuminated when desired and which could be either read on the bearing circle and/or, since it would probably be rotated by a potentiometer, conveyed directly to a repeater at the plotting table.

Similarly the range cursor might appear on the CRO screen as a circle of light which could be expanded and contracted by a knob and similarly repeated directly at the plotting table.

With a great improvement in range and bearing accuracy over that inherent in present systems, it will be undoubtedly necessary to de-

vise some method of expanded plotting to exhibit a higher order of accuracy than is now obtainable.

In any application of frequency-modulated sonars to fire control much attention will have to be given to the rapid transfer of information from the sonar stack to the fire-control computing mechanism.

8.2.10 Depth and Elevation Determination

It was only toward the end of World War II that a great deal of attention was given to the determination of vertical angles. To a large extent this arose because of the threat posed by submarines capable of operating at great depths. In visualizing the important tactical use of submarines as antisubmarine vessels, it is immediately clear that vertical angles may assume an importance which is quite equal to that of bearing angles. Therefore the future sonar must be visualized as being capable of measuring both of these angles. It would seem to be a very simple modification of standard QLA methods to rotate the transducers through 90 degrees so that they would scan in an up-and-down direction. Such vertical scanning would probably have to be conducted at quite a different frequency from the horizontal scanning in order to avoid interference. The vertical scanning frequency would probably be the higher of the two since vertical angles are of increasingly great importance as the range closes. To avoid the necessity of training such a unit in azimuth it might be arranged so that the horizontal beam patterns of both projector and hydrophone are very broad.

It will be important that vertical angle information be repeated to the plotting board and to the fire-control computing devices just as quickly and as accurately as are range and bearing information.

8.2.11 Improvements in the Transducer

As has been indicated in this report, the design of the present transducer for frequency-modulation sonar has gone hand in hand with the acquisition of basic information about and skill in the construction of transducers. Now that this understanding and experience is at hand, transducer development should progress more rapidly. New and different transducers are needed for further experimentation on different operating frequencies as well as many other parameters of a frequency-modulated sonar system.

Numerous other modifications of the transducer are called for even though the basic parameters of the system remain unchanged. There is at present too much variation in response and impedance throughout the operating band, and whereas there is some doubt that this can greatly be improved, it is still important to demonstrate some basis for this pessimism. Other modifications of the transducer have already been mentioned including such matters as arranging for the receiver to scan within the transducer case without the necessity of rotating the entire unit.

Studies of materials for use in construction of transducers should as a general measure be pursued vigorously, but in the design of any service unit more attention should be paid than has been possible in the past to such matters as corrosion resistance and the impairment of efficiency due to marine biological attachments.

GLOSSARY

BDI. Bearing deviation indicator.

B-SCOPE. A CRO indicator having a rectangular plot of range versus bearing. Spot brightness indicates echo intensity.

BTL. Bell Telephone Laboratories.

CELL-TITE. A foam rubber having isolated air bubbles.

COBAR. COntinuous Bearing And Range, designation for an experimental FM system, affording a continuous echo and a high degree of range resolution, but slow range scanning.

COMSERVRON. Commander Service Squadron, followed by squadron number.

CYCLE-WELD. A commercial rubber bonding process.

DIFFERENTIAL SENSITIVITY. The 50 per cent detectable ratio between the sum of echo strength and background noise and the background noise.

DIRECTIVITY INDEX. A measure of the directional properties of a transducer. It is the ratio, in decibels, of the average intensity or response over the whole sphere surrounding the projector or hydrophone to the intensity or response on the acoustic axis.

ECHOSCOPE. An early FM system, constructed by the Brush Development Company.

FAMPAS. Frequency And Mechanically Plotted Area Scan—the first FM system to employ a multichannel-analyzer, electronic-switch arrangement.

FLYBACK. The recycling period of the sawtooth-modulated FM oscillator.

FMO. Frequency modulated oscillator.

FOAM RUBBER. Material consisting of a mass of rubber-walled, intercommunicating air bubbles.

HYDROPHONE. An underwater microphone.

INJECTION SIGNAL. The sawtooth frequency-modulated signal introduced into the first detector circuit for heterodyning with the incoming echo signal.

LCM. Landing craft, mechanized.

LOST TIME. The period in an FM sonar, just after flyback, during which the sound field must be reestablished. Its duration equals travel time of the signal to and from the target.

MAD. Magnetic airborne detector.

MEEHANITE. Trade name for a patented iron-casting process resulting in a material that is stronger, denser, and less porous than ordinary cast iron.

MIXED LAYER. The isothermal layer, occurring at the water surface.

MOTOR, CRYSTAL. The vibrating element in a piezoelectric transducer.

NEOPRENE. Generic name for synthetic rubber made by polymerization of 2-chloro-1, 3-butadiene. Vulcanizates are markedly resistant to oils, greases, chemicals, sunlight, ozone, and heat.

ONI. Office of Naval Intelligence.

PPI. Plan position indicator.

PRIBAR. A cobar modification, utilizing the BTL supersonic prism as a hydrophone.

PRISM, BTL SUPERSONIC. A special hydrophone which can be arranged so that its acoustic axis shifts as a function of the signal frequency.

QBF. Navy designation for a particular echo-ranging system utilizing a Rochelle salt crystal transducer and a pinging technique.

QGB. Navy designation for a particular echo-ranging system, utilizing a magnetostriction transducer and incorporating BDI features.

QLA. Navy designation for FM sonar of UCDWR design.

RANGE COMPREHENSION. The difference between the minimum and maximum ranges of an FM sonar system.

RATE RANGE. Rate of change of range between own ship and target.

RANGE RESOLUTION. The minimum range separation of two targets, on the same bearing, for which the two are individually detectable.

RASTER. The rectangular pattern developed on a CRO screen by the combined effects of the horizontal and vertical sawtooth sweeps.

RECOGNITION DIFFERENTIAL. The number of db by which a signal level must exceed the background level in order to be recognized 50 per cent of the time.

REVERBERATION. Sound scattered towards the source, principally from the ocean surface or bottom, and from small scattering sources in the medium such as bubbles of air and suspended solid matter.

REVERBERATION INDEX. Measure of the ability of an echo-ranging transducer to distinguish the desired echo from the reverberation. Computed from the directivity patterns as ratio in decibels of the bottom, surface, or volume reverberation response of a specific transducer to the corresponding response of a nondirectional transducer.

ρc-RUBBER. A rubber compound with the same ρc (density $\times$ velocity of sound) product as water. Also called sound, or sound-water, rubber.

SHEAR WAVE. A transverse elastic wave propagated only in solids.

SKIATRON. A dark-trace, long-persistence cathode-ray tube which can be used for projection of plan position indication.

SLOPE AMPLIFICATION. Amplification, in FM sonar receiver amplifier, which increases uniformly with increasing frequency.

SONAR. A generic term applied to apparatus or methods that use SOund for NAvigation and Ranging.

SOUND CONDUCTIVITY COEFFICIENT. The "ρc product," in which ρ is the density of a transmitting medium and c is the velocity of sound traveling through it.

SOUNDHEAD (FM). A cylinder containing the transmitting projector and the receiving hydrophone.

SPECTRUM LEVEL (noise). Sound pressure level in a 1-cycle band.

SUBSIGHT. A fire-control sonar using cobar techniques.

TRANSDUCER. Any device for converting energy from one form to another (electrical, mechanical, or acoustic). In sonar, usually combines the functions of a hydrophone and a projector.

TRANSMISSION ANOMALY. The difference (in decibels) between the total transmission loss in intensity and the reduction in intensity due to an assumed inverse square divergence.

VARISTOR. Nonlinear resistance whose value decreases with increasing voltage.

VSO. Voltage sensitive oscillator.

X-CUT (45° X-cut). A cut in which the electrode faces of a piezoelectric crystal are perpendicular to its X-, or electric, axis. In the 45° X-cut, the longest dimension of the crystal is 45° from the Y and Z axes.

Y-CUT (45° Y-cut). A cut in which the electrode faces of a piezoelectric crystal are perpendicular to its Y-, or mechanical, axis. In the 45° Y-cut, the longest dimension of the crystal is 45° from the X and Z axes.

Z-CUT (45° Z-cut). A cut in which the electrode faces of a piezoelectric crystal are perpendicular to its Z-, or optic, axis. In the 45° Z-cut, the longest dimension of the crystal is 45° from the X and the Y axes.

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ABSTRACT:

Frequency-modulated sonar systems are discussed as to their application as underwater sound equipment. The subject is presented under the following topics: introduction to FM systems, frequency-modulated echo ranging, exploratory developmental systems, present FM (QLA-1), transducer development, developmental systems, associated devices and development . The basic job of a sonar system is the detection of submerged objects which are undetectable by any other method. In addition to mere detection the system should measure range, bearing, range rate, target aspect, depth, etc. The use of FM enables more than one target to be assimilated at a time, and two targets or more on a line but at different ranges may also be assimilated simultaneously. By use of FM the time element is reduced to 1/4th that of other known systems.

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